CHAPTER CONTENTS

CHAPTER 5. MEASUREMENT OF SURFACE WIND

5.1 GENERAL

5.1.1 Definitions

The following definitions are used in this chapter (see Mazzarella, 1972, for more details).

Wind velocity is a three-dimensional vector quantity with small-scale random fluctuations in space and time superimposed upon a larger-scale organized flow. It is considered in this form in relation to, for example, airborne pollution and the landing of aircraft. For the purpose of this Guide, however, surface wind will be considered mainly as a two-dimensional vector quantity specified by two numbers representing direction and speed. The extent to which wind is characterized by rapid fluctuations is referred to as gustiness, and single fluctuations are called gusts.

Most users of wind data require the averaged horizontal wind, usually expressed in polar coordinates as speed and direction. More and more applications also require information on the variability or gustiness of the wind. For this purpose, three quantities are used, namely the peak gust and the standard deviations of wind speed and direction.

Averaged quantities are quantities (for example, horizontal wind speed) that are averaged over a period of 10 to 60 min. This chapter deals mainly with averages over 10 min intervals, as used for forecasting purposes. Climatological statistics usually require averages over each entire hour, day and night. Aeronautical applications often use shorter averaging intervals (see Part II, Chapter 2). Averaging periods shorter than a few minutes do not sufficiently smooth the usually occurring natural turbulent fluctuations of wind; therefore, 1 min “averages” should be described as long gusts.

Peak gust is the maximum observed wind speed over a specified time interval. With hourly weather reports, the peak gust refers to the wind extreme in the last full hour.

Gust duration is a measure of the duration of the observed peak gust. The duration is determined by the response of the measuring system. Slowly responding systems smear out the extremes and measure long smooth gusts; fast response systems may indicate sharp wave-front gusts with a short duration.

For the definition of gust duration an ideal measuring chain is used, namely a single filter that takes a running average over t_0 seconds of the incoming wind signal. Extremes detected behind such a filter are defined as peak gusts with duration t_0. Other measuring systems with various filtering elements are said to measure gusts with duration t_0 when a running average filter with integration time t_0 would have produced an extreme with the same height (see Beljaars, 1987; WMO, 1987 for further discussion).

Standard deviation is:

$$s_u = \sqrt{\overline{(u_i - U)^2}} = \sqrt{\left(\left(\Sigma\left(u_i^2\right) - \left(\Sigma u_i\right)^2 / n\right) / n\right)} \qquad (5.1)$$

where u is a time-dependent signal (for example, horizontal wind speed) with average U and an overbar indicates time-averaging over n samples u_i. The standard deviation is used to characterize the magnitude of the fluctuations in a particular signal.

Time constant (of a first-order system) is the time required for a device to detect and indicate about 63% of a step-function change.

Response length is approximately the passage of wind (in metres) required for the output of a wind-speed sensor to indicate about 63% of a step-function change of the input speed.

Critical damping (of a sensor such as a wind vane, having a response best described by a second-order differential equation) is the value of damping which gives the most rapid transient response to a step change without overshoot.

Damping ratio is the ratio of the actual damping to the critical damping.

Undamped natural wavelength is the passage of wind that would be required by a vane to go through one period of an oscillation if there were no damping. It is less than the actual "damped" wavelength by a factor $\sqrt{(1-D^2)}$ if D is the damping ratio.

Variable wind with no mean wind direction is wind where the total variation from the mean wind direction during the previous 10 minutes is 60° or more, and less than 180°, and the wind speed is less than 6 km/h (3 kt), or when the total variation is 180° or more.

5.1.2 **Units and scales**

Wind speed should be reported to a resolution of 0.5 m s^{-1} or in knots (0.515 m s^{-1}) to the nearest unit, and should represent, for synoptic reports, an average over 10 min. Averages over a shorter period are necessary for certain aeronautical purposes (see Part II, Chapter 2).

In traditional codes, wind direction should be reported in degrees true to the nearest 10°, using a 01 ... 36 code (for example, code 2 means that the wind direction is between 15° and 25°), and should represent an average over 10 min (see Part II, Chapter 2). In BUFR code, wind direction should be reported in degrees true, with resolution 1°. Wind direction is defined as the direction from which the wind blows, and is measured clockwise from geographical north, namely, true north (based on the World Geodetic System 1984 (WGS-84) and its Earth Geodetic Model 1996 (EGM96)).

"Calm" should be reported when the average wind speed is less than 1 kt. The direction in this case is coded as 00.

Wind direction at stations within 1° of the North Pole or 1° of the South Pole should be measured so that the azimuth ring should be aligned with its zero coinciding with the Greenwich 0° meridian.

5.1.3 **Meteorological requirements**

Wind observations or measurements are required for weather monitoring and forecasting, for wind-load climatology, for probability of wind damage and estimation of wind energy, and as part of the estimation of surface fluxes, for example, evaporation for air pollution dispersion and agricultural applications. Performance requirements are given in Part I, Chapter 1, Annex 1.E. An accuracy for horizontal speed of 0.5 m s^{-1} below 5 m s^{-1} and better than 10% above 5 m s^{-1} is usually sufficient. Wind direction should be measured with an accuracy of 5°. Apart from mean wind speed and direction, many applications require standard deviations and extremes (see section 5.8.2). The required accuracy is easily obtained with modern instrumentation. The most difficult aspect of wind measurement is the exposure of the anemometer. Since it is nearly impossible to find a location where the wind speed is representative of a large area, it is recommended that estimates of exposure errors be made (requirements on siting and exposure are provided in section 5.9 and in Part I, Chapter 1, Annex 1.B).

Many applications require information about the gustiness of the wind. Such applications provide "nowcasts" for aircraft take-off and landing, wind-load climatology, air pollution dispersion problems and exposure correction. Two variables are suitable for routine reading, namely the standard deviation of wind speed and direction and the 3 s peak gust (see Recommendations 3 and 4 (CIMO-X) (WMO, 1990)).

5.1.4 **Methods of measurement and observation**

Surface wind is usually measured by a wind vane and cup or propeller anemometer. When the instrumentation is temporarily out of operation or when it is not provided, the direction and force of the wind may be estimated subjectively (Tables 5.1 and 5.2 provide wind speed equivalents in common use for estimations).

The instruments and techniques specifically discussed here are only a few of the more convenient ones available and do not comprise a complete list. The references and further reading at the end of this chapter provide a good literature on this subject.

The sensors briefly described below are cup-rotor and propeller anemometers, and direction vanes. Cup and vane, propeller and vane, and propellers alone are common combinations. Other classic sensors, such as the pitot tube, are less used now for routine measurements but can perform satisfactorily, while new types being developed or currently in use as research tools may become practical for routine measurement with advanced technology.

Table 5.1. Wind speed equivalents

Beaufort scale number and description		*Wind speed equivalent at a standard height of 10 m above open flat ground*				*Specifications for estimating speed over land*
		(kt)	*(m s^{-1})*	*(km h^{-1})*	*(mi h^{-1})*	
0	Calm	< 1	0 – 0.2	< 1	< 1	Calm; smoke rises vertically
1	Light air	1 – 3	0.3 – 1.5	1 – 5	1 – 3	Direction of wind shown by smoke-drift but not by wind vanes
2	Light breeze	4 – 6	1.6 – 3.3	6 – 11	4 – 7	Wind felt on face; leaves rustle; ordinary vanes moved by wind
3	Gentle breeze	7 – 10	3.4 – 5.4	12 – 19	8 – 12	Leaves and small twigs in constant motion; wind extends light flag
4	Moderate breeze	11 – 16	5.5 – 7.9	20 – 28	13 – 18	Raises dust and loose paper; small branches are moved
5	Fresh breeze	17 – 21	8.0 – 10.7	29 – 38	19 – 24	Small trees in leaf begin to sway, crested wavelets form on inland waters
6	Strong breeze	22 – 27	10.8 – 13.8	39 – 49	25 – 31	Large branches in motion; whistling heard in telegraph wires; umbrellas used with difficulty
7	Near gale	28 – 33	13.9 – 17.1	50 – 61	32 – 38	Whole trees in motion; inconvenience felt when walking against the wind
8	Gale	34 – 40	17.2 – 20.7	62 – 74	39 – 46	Breaks twigs off trees; generally impedes progress
9	Strong gale	41 – 47	20.8 – 24.4	75 – 88	47 – 54	Slight structural damage occurs (chimney-pots and slates removed)
10	Storm	48 – 55	24.5 – 28.4	89 – 102	55 – 63	Seldom experienced inland; trees uprooted; considerable structural damage occurs
11	Violent storm	56 – 63	28.5 – 32.6	103 – 117	64 – 72	Very rarely experienced; accompanied by widespread damage
12	Hurricane	64 and over	32.7 and over	118 and over	73 and over	

Table 5.2. Wind speed equivalents for arctic areas and areas where there is no vegetation

Beaufort scale number and description		*Wind speed equivalent at a standard height of 10 m above open flat ground*				*Specifications for estimating speed for arctic areas and areas where there is no vegetation*
		(kt)	*(m s^{-1})*	*(km h^{-1})*	*(mi h^{-1})*	
0	Calm	< 1	0 – 0.2	< 1	< 1	
1	Light air	1 – 3	0.3 – 1.5	1 – 5	1 – 3	No noticeable wind; smoke rises nearly vertically
2	Light breeze	4 – 6	1.6 – 3.3	6 – 11	4 – 7	Wind felt on face, leaves rustle
3	Gentle breeze	7 – 10	3.4 – 5.4	12 – 19	8 – 12	Hair is disturbed, clothing flaps
4	Moderate breeze	11 – 16	5.5 – 7.9	20 – 28	13 – 18	Dust and loose paper raised, hair disarranged
5	Fresh breeze	17 – 21	8.0 – 10.7	29 – 38	19 – 24	Force of wind felt on body; limit of agreeable wind on land
6	Strong breeze	22 – 27	10.8 – 13.8	39 – 49	25 – 31	Some inconvenience in walking
7	Near gale	28 – 33	13.9 – 17.1	50 – 61	32 – 38	Difficulty when walking against wind
8	Gale	34 – 40	17.2 – 20.7	62 – 74	39 – 46	Difficulty with balance in walking
9	Strong gale	41 – 47	20.8 – 24.4	75 – 88	47 – 54	Danger in being blown over
10	Storm	48 – 55	24.5 – 28.4	89 – 102	55 – 63	Trees uprooted, considerable structural damage
11	Violent storm	56 – 63	28.5 – 32.6	103 – 117	64 – 72	
12	Hurricane	64 and over	32.7 and over	118 and over	73 and over	

For nearly all applications, it is necessary to measure the averages of wind speed and direction. Many applications also need gustiness data. A wind-measuring system, therefore, consists not only of a sensor, but also of a processing and recording system. The processing takes care of the averaging and the computation of the standard deviations and extremes. In its simplest form, the processing can be done by writing the wind signal with a pen recorder and estimating the mean and extreme by reading the record.

5.2 ESTIMATION OF WIND

In the absence of equipment for measuring wind, the observations must be made by estimation. The errors in observations made in this way may be large, but, provided that the observations are used with caution, the method may be justified as providing data that would otherwise not be available in any way. If either temporarily or permanently the wind data of some stations are obtained by estimation instead of measurement, this fact should be documented in station records made accessible to data users.

5.2.1 Wind speed

Estimates are based on the effect of the wind on movable objects. Almost anything which is supported so that it is free to move under the influence of the wind can be used, but the descriptive specifications given in the Beaufort scale of wind force, as reproduced in the tables, will be found especially useful.

In order to make the estimates, the observer (and the wind-susceptible object) must stand on flat open terrain as far as possible from obstructions. It must always be remembered that even small obstructions cause serious changes in wind speed and deviations in wind direction, especially at their lee side.

5.2.2 Wind direction

In the case of an absence of instruments, or when the instrumental equipment is unserviceable, the direction should be estimated by observing the drift of smoke from an elevated chimney, the movement of leaves, and so on, in an open situation, or a streamer or pennant fixed to a tall flagstaff. In addition, the wind drogue at an airport may be used when the wind speed is sufficient to move such a device.

Whichever of these aids is used, errors due to perspective are liable to be made unless the observer stands vertically below the indicator. Care should be taken to guard against mistaking local eddies caused by buildings, and the like, for the general drift of the wind.

In an open location, the surface wind direction can be estimated rather accurately by facing the wind. The direction of the movement of clouds, however low, should not be taken into account.

5.2.3 Wind fluctuations

No attempt should be made to estimate peak gusts or standard deviations without proper instruments and recording devices.

5.3 SIMPLE INSTRUMENTAL METHODS

At stations where orthodox anemometers cannot be installed it may be possible to provide some very low-cost, simple instruments that help the observer take measurements that are somewhat more reliable than those obtained by unaided estimation.

5.3.1 Wind speed

Simple hand-held anemometers, if they are used, should be set up and read in accordance with the maker's instructions. The measurement should be taken from a point well exposed to the wind, and not in the lee of obstructions such as buildings, trees and hillocks. If this is not possible, the measurement point should be a good distance from obstructions, namely at least 10 times the obstruction height and upwind or sideways by at least twice the obstruction height.

5.3.2 Wind direction

Direction may be estimated from a vane (or banner) mounted on a pole that has pointers indicating the principal points of the compass. The vane is observed from below, and wind direction may be estimated to the nearest of the 16 points of the compass. If the vane oscillates in the wind, the wind direction must be estimated as the average direction about which the oscillations occur.

5.4 CUP AND PROPELLER SENSORS

Cup and propeller anemometers are commonly used to determine wind speed and consist of two sub-assemblies: the rotor and the signal generator. In well-designed systems, the angular velocity of the cup or propeller rotor is directly proportional to the wind speed, or, more precisely, in the case of the propeller rotor, to the component of the wind speed parallel to the axis of rotation. Also, in well-designed anemometers, the calibration linearity is independent of air density, has good zero and range stability, and is easily reproduced in a manufacturing process. Near the starting threshold, say for wind speeds of less than 4 m s^{-1}, the calibration of cup anemometers can deviate substantially from linearity, if the arm connecting the cup to the rotation axis is much longer than the diameter of the cup (Patterson, 1926).

The nature of the response of the cup and propeller-type wind-speed sensors to changes in wind speed can be characterized by a response length, the magnitude of which is directly proportional to the moment of inertia of the rotor and, in addition, depends on a number of geometric factors (Busch and Kristensen, 1976; Coppin, 1982).

For almost all cup and propeller-type wind sensors, the response is faster for acceleration than for deceleration, so that the average speed of these rotors overestimates the actual average wind speed. Moreover, vertical velocity fluctuations can cause overspeeding of cup anemometers as a result of reduced cup interference in oblique flow (MacCready, 1966). The total overspeeding can be as much as 10% for some designs and turbulent wind conditions (cup anemometers at 10 m height with a response length of 5 m over very rough terrain; Coppin, 1982). This effect can be minimized by choosing fast-response anemometers, either cup anemometers of a design verified as having a good cosine response or propeller vanes that have virtually no vertical component of overspeeding. In case that performance cannot be investigated in a wind tunnel, operational anemometers can be compared in the field with a calibrated anemometer (Albers et al., 2000).

Since both cup and propeller rotors turn with an angular velocity that is directly proportional to speed or to the axial component, they are particularly convenient for driving a wide variety of signal generators. Alternating and direct current generators, optical and magnetic pulse generators, and turn-counting dials and registers have been used (WMO, 2001). The choice of signal generator or transducer depends largely on the type of data processor and read-out to be used. Care should be taken to ensure that the bearings and signal generator have low starting and running frictional torques, and that the moment of inertia of the signal generator does not reduce the response too much. In cases of long-distance transmission, voltage signals decrease due to cable resistance losses and are therefore inferior to pulse frequency signals, which are not so affected during transmission.

The required and achievable characteristics for wind-speed sensors are included in Part I, Chapter 1, Annex 1.E.

5.5 WIND-DIRECTION VANES

For the purpose of obtaining a satisfactory measurement, a wind vane will be suitable if it is well balanced so as not to have a preferred position in case the axis is not vertical. Multiple vane fins should preferably be parallel to the vane axis, because a vane with two fins at angles > 10° to its axis has two equilibrium positions which each differ significantly from the real wind direction (Wieringa and van Lindert, 1971).

The response of the usual underdamped wind vane to a sudden change in wind direction is normally characterized by overshoot and oscillation about its true position, with the amplitude decreasing approximately exponentially. Two variables are used to define this response: the "undamped natural frequency" or "wavelength" and the "damping ratio", the ratio of the actual damping to the critical damping (MacCready, 1966; Mazzarella, 1972). A damping ratio between 0.3 and 0.7 is considered to be good and as having not too much overshoot, and a reasonably fast response (Wieringa, 1967). Where a relatively long period average is to be computed from data captured at short intervals, it is self-evident that lower damping ratios may be acceptable.

The signal generator is essentially a shaft-angle transducer, and many varieties have been employed. Potentiometers, alternating and direct current synchros, digital angle-encoder discs, direct reading dials and rotary switches have been used to advantage. The choice of signal generator is largely a matter of the type of data processor and read-out used. Care should be taken to ensure that the bearings and signal generator have low starting and running frictional torques. The simplest recording method is to have a sheet mounted around a cylinder rotating with the vane axis, on which a writing instrument slowly travels downward.

The absolute accuracy of direction measurement also depends on the care with which the instrument has been aligned to true north. The required and achievable characteristics for wind-direction vanes are included in Part I, Chapter 1, Annex 1.E.

5.6 OTHER WIND SENSORS

Many physical principles can be used to measure wind speed and direction, all of which have their own merits and problems. New systems often have been developed for specific purposes, such as small-scale fluctuations and air pollution studies (see for example, Smith (1980)). The following are other types of sensors:

(a) Pitot tube anemometers, which measure the overpressure in a tube that is kept aligned with the wind vector by means of a direction vane (see Gold (1936) and WMO (1984*a*) for a description of the Dines anemometer). The Dines linearizing recording system deals with the speed averaging problem caused by the quadratic relation between wind speed and pressure, and it also provides useful gustiness records without requiring electrical power;

(b) Sonic anemometers, which measure the time between emission and reception of an ultrasonic pulse travelling over a fixed distance (Kaimal, 1980). Because sonic anemometers have no moving parts owing to their principle, they have high durability and little accuracy deterioration;

(c) Hot-disc anemometers are recently developed solid-state instruments which measure the temperature gradient across a chip arrangement. This provides both wind speed and direction at accuracies within the specification of Part I, Chapter 1, Annex 1.E (Van Oudheusden and Huijsing, 1991; Makinwa et al., 2001). They are sturdy, and steady in calibration, but operational experience is limited so far;

(d) Hot-wire anemometers measure the cooling of thin heated wires. Operationally they are rather unreliable, both because of excessive fragility and because their calibration changes rather fast in unclean or wet surroundings. They are not recommended for use in precipitation;

(e) Antique swinging-plate vanes are a little better than no instrument at all;

(f) Remote wind-sensing techniques with sound (sodar), light (lidar) or electromagnetic waves (radar) are uncommon in routine meteorological networks and will not be discussed in this Guide. Details are provided in Lenschow (1986).

5.7 SENSORS AND SENSOR COMBINATIONS FOR COMPONENT RESOLUTION

Propellers which respond only to the wind speed component that is parallel to the axis of rotation of the rotor can be mounted orthogonally to produce two read-outs which are directly proportional to the components in the axis directions. Other sensors, such as twin-axis sonic anemometers, perform the same function at the expense of more sophisticated electronic adjuncts. Orthogonal propellers have the disadvantage that exact cosine response (namely, pure component sensitivity) is difficult to attain. A cup anemometer/vane combination or a propeller vane can also be used as a component device when the velocity components are computed from the measured wind speed and direction.

5.8 DATA-PROCESSING METHODS

Signals from anemometer/vane combinations can be processed and averaged in many different ways. Before considering the aspects of the entire wind-measuring chain (exposure, sensing, transmission, filtering, recording and processing), it is useful to discuss the problem of averaging. This Guide deals with the following outputs: averaged horizontal wind (components or speed/direction), standard deviations and peak gust.

5.8.1 Averaging

The averaging of wind vectors or their components is straightforward in principle, but there are a few problems associated with it. The first is that the mean vector speed in the average wind direction U is less than the average of all instantaneous wind speeds by a small amount, generally a few % (MacCready, 1966; Wieringa, 1980*a*). If necessary, this may be corrected if the standard deviation of wind direction s_d is measured; for the ratio of U, and the averaged instantaneous wind speeds is (Frenkiel, 1951):

$$U \Big/ \overline{\sqrt{\left(u_i^2 + v_i^2\right)}} = 1 - s_d^2 / 2 \tag{5.2}$$

This effect of crosswind turbulence is often confused with the overestimation (overspeeding), causing distortion in the standard deviation s_u (see section 5.4).

The second problem is the discontinuity of the wind direction between 0° and 360°. This problem can be solved either by recording on a cylinder or by extending the recorder range (for example to 540° with an automatic device switching the range from 0 to 360 and from 540 to 180), or by a computer algorithm that makes successive samples continuous by adding or subtracting 360° when necessary. The fact that the first-order response of a cup anemometer and the second-order response of a vane cannot be fully matched is a problem of minor importance, because the response differences are reflected only in the high-frequency part of the fluctuations.

From the fundamental point of view, component averaging is preferable over the independent averaging of speed and direction. However, the differences are very small and, for most applications, component averages can easily be derived from average speed and direction. This also applies to the corresponding standard deviations. From the technical point of view, the independent treatment of speed and direction is preferable for a number of reasons. First of all, the processing of the signal for speed and direction is independent, which implies that the operation of one instrument can continue even when the other drops out. Secondly, this data reduction is simpler than in those cases where components have to be computed. Lastly, the independent treatment of speed and direction is compatible with common usage (including SYNOP and SHIP coding).

The averages of horizontal wind speed can be obtained with a number of both mechanical and electrical devices. Perhaps the simplest example is a mechanical rotation-counting register on a cup anemometer commonly used to measure the passage of wind during a chosen averaging time interval. At the other end of the complexity spectrum, electrical pulse generators drive special-purpose digital processors, which can easily calculate averages, peak gusts and standard deviations.

If wind speed and direction are recorded as continuous graphs, an observer can estimate 10 min averages fairly accurately from a pen recording. The recorded wind trace can also be used to read peak gusts. The reading of dials or meters gives a feel for the wind speed and its variability, but is subject to large errors when averages are needed. Instantaneous read-outs are, therefore, less suitable to obtain 10 min averages for standard weather reports.

5.8.2 Peak gusts and standard deviations

The computation or recording of wind fluctuations is extremely sensitive to the dynamic response of all the elements of the measuring chain, including response length and damping ratio of the sensors. Additionally, the dynamic response of the system as a whole determines the duration of peak gusts, as defined in section 5.1.1. Slowly responding systems spread out the extremes and indicate wide gusts with small amplitude, whereas fast-response systems record high and narrow peaks (gusts of short duration). It is clear that the dynamic response of wind systems has to be carefully designed to obtain gusts or standard deviations that are accurate, reliable and compatible between stations.

Before specifying the appropriate response characteristics of wind-measuring systems, it is necessary to define the gust duration as required by the application. Wind extremes are mainly used for warning purposes and for the climatology of extreme loads on buildings, constructions and aircraft. It is important to realize that the shortest gusts have neither the time nor the horizontal extent to exert their full damaging effect on large constructions. WMO (1987) concludes that a gust duration of about 3 s accommodates most potential users. Gusts that persist for about 3 s correspond to a “wind run” (duration multiplied by the average wind speed) of the order of 50 to 100 m in strong wind conditions. This is sufficient to engulf structures of ordinary suburban/urban size and to expose them to the full load of a potentially damaging gust.

The standard deviation of wind direction and wind speed can easily be computed with microcomputer-based equipment by taking samples of the signals at intervals of about 1 s. Sampling frequencies should not be too great, because the sensor itself provides smoothing over a multiple of its response distance (Wieringa, 1980*b*). A sampling frequency of 0.25 Hz is suitable in most cases, but depends on the response distance of the sensor and the wind speed. Part IV, Chapter 2, includes a detailed discussion of the theory of sampling sensor signals.

Simultaneous computation of the standard deviation of the horizontal wind speed over 10 min together with the detection of gusts with a duration of a few seconds gives interesting requirements for electronic filters. The gusts are most critical with regard to filtering, so in practice the system is optimized for them. Any low-pass filter used for the detection of peak gusts measured by fast anemometers, smoothing over a few seconds, may reduce the standard deviation by up to 10%. This can be corrected if the filtering variables in the measuring chain are well documented. Often, in practice, the reduction is less because the standard deviation increases if the average wind speed shows a positive or negative trend. Alternatively, the unfiltered signal can be recorded separately for the purpose of measuring an unbiased standard deviation. In the next section, recommendations are made for wind-measuring systems with exact values for the filter variables.

In order to determine peak gusts accurately, it is desirable to sample the filtered wind signal every 0.25 s (frequency 4 Hz). Lower sampling frequencies can be used, but it should be realized that the estimate of the extreme will generally be lower as the extreme in the filtered signal may occur between samples.

Apart from the wind vane inertial damping, any further filtering should be avoided for wind direction. This means that the standard deviation of wind direction can be determined within 2% with most wind vanes.

Accurate computation of the standard deviation of wind direction requires a minimum resolution of the digitization process, which is often done on the shaft of the vane by means of a digital encoder. A 7 bit resolution is quite sufficient here because then a 5° unit for the standard deviation can still be measured with an accuracy of 1% (WMO, 1987).

5.8.3 Recommendations for the design of wind-measuring systems[1]

Wind-measuring systems can be designed in many different ways; it is impossible to cover all design options in this Guide. Two common examples are given here, one with mainly analogue signal treatment and the other with digital signal processing (WMO, 1987).

The first system consists of an anemometer with a response length of 5 m, a pulse generator that generates pulses at a frequency proportional to the rotation rate of the anemometer (preferably several pulses per rotation), a counting device that counts the pulses at intervals of 0.25 s, and a microprocessor that computes averages and standard deviation over 10 min intervals on the basis of 0.25 s samples. The extreme has to be determined from 3 s averages, namely, by averaging over the last 12 samples. This averaging has to be done every 0.25 s (namely, overlapping 3 s averages every 0.25 s). The wind direction is measured with a vane that has an undamped wavelength of 5 m, a damping ratio of 0.3, and a 7 bit digital encoder that is sampled every second. Averages and standard deviations are computed over 10 min intervals, where successive samples are checked for continuity. If two successive samples differ by more than 180°, the difference is decreased by adding or subtracting 360° from the second sample. With response lengths of 5 m for the anemometer and the wind vane (damping ratio 0.3, undamped wavelength 10 m), the standard deviations of wind speed and wind direction are reduced by about 7% and 2%, respectively. The gust duration corresponding to the entire measuring chain (as defined in section 5.1.1) is about 3 s.

The second system consists of an anemometer with a response length of 5 m, a voltage generator producing a voltage proportional to the rotation rate of the anemometer, analogue-to-digital conversion every second, and the digital processing of samples. The wind-direction part consists of a vane with an undamped wavelength of 5 m and a damping ratio of 0.3, followed by analogue-to-digital conversion every second and digital computation of averages and standard deviations. To determine peak gusts the voltage is filtered with a first-order filter with a time constant of 1 s and analogue-to-digital conversion every 0.25 s. With regard to filtering, this system is slightly different from the first one in that standard deviations of wind speed and direction are filtered by 12% and 2%, respectively, while again the gust duration is about 3 s. This system can also be operated with a pen recorder connected to the analogue output instead of the analogue-to-digital converter. Only averages and extremes can be read now, and the gust duration is about 3 s, unless the pen recorder responds more slowly than the first-order filter.

The signal-processing procedure, as described above, is in accordance with Recommendation 3 (CIMO-X) (WMO, 1990) and guarantees optimal accuracy. The procedure, however, is fairly complicated and demanding as it involves overlapping averages and a relatively high sampling frequency. For many applications, it is quite acceptable to reduce the sampling rate down to one sample every 3 s, provided that the wind signal has been averaged over 3 s intervals (namely, non-overlapping averaging intervals). The resulting gust duration is about 5 s and the reduction in standard deviation is 12% (Beljaars, 1987; WMO, 1987).

5.9 EXPOSURE OF WIND INSTRUMENTS

5.9.1 General problems

Wind speed increases considerably with height, particularly over rough terrain. For this reason, a standard height of 10 m above open terrain is specified for the exposure of wind instruments. For wind direction, the corresponding shift over such a height interval is relatively small and can be ignored in surface wind measurements. An optimum wind observation location is one where the observed wind is representative of the wind over an area of at least a few kilometres, or can easily be corrected to make it representative.

For terrain that is uneven, contains obstacles, or is non-homogeneous in surface cover, both wind speed and direction can be affected considerably. Corrections are often possible, and the tools

[1] Recommended by the Commission for Instruments and Methods of Observation at its tenth session (1989).

to compute such corrections are becoming available. To improve the applicability of wind data, essential information to perform such corrections should be transmitted to the users in addition to the direct measurements.

5.9.2 Anemometers over land

The standard exposure of wind instruments over level, open terrain is 10 m above the ground. Open terrain is defined as an area where the distance between the anemometer and any obstruction is at least 10 times the height of the obstruction. Wind measurements that are taken in the direct wake of tree rows, buildings or any other obstacle are of little value and contain little information about the unperturbed wind. Since wakes can easily extend downwind to 12 or 15 times the obstacle height, the requirement of 10 obstruction heights is an absolute minimum. In practice, it is often difficult to find a good or even acceptable location for a wind station. The importance of optimizing the location can hardly be overstressed; nonetheless, it is difficult to give universal guidelines. In some cases, however, the data can be largely corrected for obstructions, as follows:

(a) Obstacles at a distance of more than 30 times their height: no correction needs to be applied;

(b) Obstacles at a distance of more than 20 times their height: correction can be applied;

(c) Obstacles at a distance of more than 10 times their height: correction may be applied in some situations, taking special care.

It should be noted that when the distance is less than 20 times the height of the obstacle, the measured value before correction can be erroneous by up to 25%; when the distance is about 10 times the height of the obstacle, the measured value can in some cases even indicate the opposite direction.

Detailed information on the exposure correction is provided in paragraph 5.9.4.

In Table 5.3, the classification of wind observing sites based on siting and exposure is summarized. Full details on the siting classification for surface observing stations on land, which provides additional guidance on the selection of a site and the location of a wind sensor within a site to optimize representativeness, can be found in Part I, Chapter 1, Annex 1.B of this Guide.

Table 5.3. Classification of wind observing sites based on siting and exposure

Class	*Distance of mast to surrounding obstacles[a] (with height h)*	*Distance of sensors to thin obstacles[b] (with height > 8 m, width w)*	*Roughness class index[c]*	*Ignore single obstacles below x m*
1	≥ 30 h	≥ 15 w	2 – 4 (roughness length ≤ 0.1 m)	$x = 4$
2	≥ 10 h	≥ 15 w	2 – 5 (roughness length ≤ 0.25 m)	$x = 4$
3	≥ 5 h	≥ 10 w		$x = 5$
4	≥ 2.5 h	No obstacle with angular width > 60° and height > 10 m within 40 m distance		$x = 6$, if measurement at ≥ 10 m
5	Not meeting requirements of any other class			

Notes:
a An obstacle is defined as an object having an angular width > 10°.
b A thin obstacle is for instance a mast, thin tree or lamp post.
c Roughness is defined in the annex of this chapter.

Two aspects are very important. First, the sensors should be kept away from local obstructions as much as possible. When wind measurements are taken on the side of masts or towers rather than at their top, the instruments should be placed on booms with a length of at least three mast or tower widths (Gill et al., 1967). When wind instruments are placed on top of a building, they should be raised at least one building width above the top. Secondly, the local situation should be well documented (Wieringa, 1983). There should at least be a map of the station surroundings within a radius of 2 km, documenting obstacle and vegetation locations and height, terrain elevation changes, and so forth. Changes in the surroundings, such as the construction of buildings or growth of trees nearby, should be explicitly recorded in station logbooks. Station instrumentation should be specified in detail.

Where standard exposure is unobtainable, the anemometer may be installed at such a height that its indications should not be too much affected by local obstructions and represent as far as possible how the wind at 10 m would be if there were no obstructions in the vicinity. If the terrain varies little with azimuth, this may be effected by placing the anemometer at a height exceeding 10 m by an amount depending on the effective surface roughness length z_0 of the surroundings (see the annex): about 13 m if $z_0 = 0.1$ m, and about 19 m if $z_0 = 0.5$ m. Wieringa (1980*b*) shows that the strategy of anemometer height increase does not work well if local sheltering varies strongly with azimuth. Simple calculation procedures now exist to determine the effect of local topography (Walmsley et al., 1990), and the climatology of the gustiness records can be used to determine exposure corrections in inhomogeneous surroundings (Verkaik, 2000). Evans and Lee (1981) and Grimmond et al. (1998) discuss the problem in urban areas (see also Part II, Chapter 9).

In freezing weather, special precautions must be taken to keep the wind sensors free from sleet and ice accumulations. In some localities it may be desirable to provide some form of artificial heating for the exposed parts such as a thermostatically controlled infrared radiator. Sleet and ice shields have been designed for particular types of wind equipment (see Curran et al., 1977).

5.9.3 Anemometers at sea

There is an increasing requirement for instrumental measurements of wind over the sea, especially by means of automatic unattended systems (see also Part II, Chapter 4). This task presents special problems since the standard exposure height of 10 m specified for land use cannot always be achieved in a marine environment owing to the state of the sea and/or tidal height variation. The obvious extrapolation of the exposure criteria for land sites leads to the idea that, on moored buoys, the anemometer should be mounted 10 m above the waterline of the buoy. However, other sources of error are often more significant than those arising from different exposure heights (for a review, see WMO, 1981). On fixed platforms and ships, it is of the utmost importance that wind sensors be exposed sufficiently high above the platform and its superstructure to avoid the often extensive influence of the platform on the local wind structure. In general, it is never safe to assume that a wind sensor is unaffected by the platform structure, even if it is exposed at least 10 m above the height of the tallest obstruction on the platform, unless the platform is relatively small. WMO (1981) concludes that, at sea, good exposure should have higher priority in obtaining accurate and useful measurements than standardization of the measurements at 10 m (WMO, 1989). Despite careful siting, it is often impossible in practice to avoid exposure errors. In order to allow height and flow distortion corrections to be made, it is very important to keep a record and detailed information about anemometer location and platform or ship type (shape, dimension). If wind speed is measured at a height significantly greater than 10 m (namely, when the appropriate reduction factor would be > 1.2), a reduction to the 10 m level should be performed according to the procedures recommended in the following paragraph, and using the constant for “open sea” in the table of the annex.

5.9.4 Exposure correction

Surface wind measurements without exposure problems hardly exist. The requirement of open, level terrain is difficult to meet, and most wind stations over land are perturbed by topographic effects or surface cover, or by both (WMO, 1987; Wieringa, 1996).

It is clear that exposure errors pose problems to users of wind data and often make the data useless. This problem is particularly serious in numerical forecast models where there is a tendency to analyse the wind and pressure fields separately. Surface winds, however, can be used for initialization only if they are representative of a large area. This means that errors due to local exposure and/or non-standard measurement height must be removed.

The correction of wind readings for local exposure can be performed only with measurements of reasonable quality at locations that are not too rough ($z_0 \leq 0.5$ m) and reasonably level. No attempt should be made to correct measurements that have hardly any relation to a regional average. For example, a wind station in a deep valley, where the flow is dominated by katabatic effects, may be important for local forecasts, but cannot be used as a regionally representative wind.

If U is the wind speed measured at height z, the corrected wind speed U_c which would be indicated locally at 10 m above terrain with roughness z_0 follows from:

$$U_c = U \cdot C_F \cdot C_T \cdot \frac{\ln(10/z_{0u})}{\ln(z/z_{0u})} \cdot \frac{\ln(60/z_{0u})\ln(10/z_0)}{\ln(10/z_{0u})\ln(60/z_0)} \tag{5.3}$$

where C_F is the flow distortion correction; C_T is the correction factor due to topographic effects; z_{0u} is the effective roughness length of the terrain upstream of the measurement station, and z_0 is roughness length in the application (for example, a grid box value in a numerical forecast model). In this expression, z, z_0 and z_{0u} are specified in metres. The different correction terms represent the following:

(a) Flow distortion: The correction factor C_F accounts for flow distortion by nearby big objects. This is particularly important for anemometers on buildings, ships, and platforms at sea. The best way of finding C_F as a function of wind direction is by means of model simulation in a wind tunnel (Mollo-Christensen and Seesholtz, 1967). Estimates based on potential flow around simple configurations can also be applied (Wyngaard, 1981; WMO, 1984*b*). For measurements on top of a free-standing mast, flow distortion is negligible ($C_F = 1$).

(b) Topographic correction: This correction accounts for terrain height effects around the wind station. C_T is the ratio of the regionally averaged wind speed (averaged over ridges and valleys at 10 m above local terrain) and the wind speed measured at the wind station. In the example of an isolated hill with a station at the top of the hill, C_T should be less than 1 to correct for the speed-up induced by the hill, to make the result representative of the area rather than of the hill top only. C_T equals 1 for flat terrain. For isolated hills and ridges, estimates of C_T can be made with the help of simple guidelines (Taylor and Lee, 1984). In more complicated topography, model computations are needed on the basis of detailed height contour maps of the terrain surrounding the wind stations (Walmsley et al., 1990). Such computations are fairly complicated but need to be done only once for a single station and lead to a semi-permanent table of C_T as a function of wind direction.

(c) Non-standard measurement height: This effect is simply included in the U_c formula by assuming a logarithmic profile combined with the roughness length z_{0u} of the upstream terrain. For stations over sea, this reduction to standard height can be important, but stability corrections are relatively small there, justifying the logarithmic form of the reduction.

(d) Roughness effects: Upstream roughness effects as well as the effects of surface obstacles can be corrected by extrapolating the wind speed logarithmic profile to a height of 60 m with the station specific effective roughness length z_{0u} and by interpolating back to 10 m with the roughness length z_0 necessary for the application. The roughness length z_{0u} should be representative of a 2 km fetch upwind of the wind station; the value usually depends on wind direction. The annex discusses how to estimate z_{0u}.

If flow distortion and topography problems are negligible or have been corrected, apply the (c) to (d) exposure correction by formula 5.3 towards $z = 10$ m and $z_0 = 0.03$ m. Corrected wind speeds then will be equivalent to those which would have been measured at a local hypothetical wind station conforming fully with WMO requirements (10 m over open terrain). Wind speeds corrected in this way are called potential wind speeds (WMO, 2001). Two comments are appropriate here. First, the extrapolation height of 60 m should not be seen as a very firm value. Heights between 40 and 80 m would have been acceptable; 60 m is about the correct magnitude in relation to the 2 km fetch for which z_{0u} is representative and has proved to give satisfactory results (Wieringa, 1986). Secondly, stability-related changes in the wind profile cannot be neglected over the height range from 10 to 60 m, but the effect of stability is relatively small in the present formulation because the stability corrections in the transformations upwards and downwards cancel out. A practical example of the application of wind measurement correction in an operational context is given in WMO (2000) and WMO (2001). Although most of the exposure correction can be directly applied to the measurements, both unadjusted (Level I) data and adjusted (Level II) data are to be disseminated.

5.10 CALIBRATION AND MAINTENANCE

A fully reliable calibration of cup, propeller and vane anemometers is possible only in a wind tunnel; the performance of such instruments is now well known and the manufacturer's calibration can be relied upon for most purposes, when the instrument is in good condition. Wind-tunnel tests are useful for special projects or for type-testing new models. For more information, see the International Organization for Standardization (ISO) standards (ISO 16622:2002 and ISO 17713-1:2007).

In the field, anemometers are prone to deterioration and regular inspections are advisable. A change in sensor characteristics leading to a deterioration in wind data quality may occur as a result of physical damage, an increase in bearing friction from the ingress of dust, corrosion, or degradation of the transduction process (for example, a reduction in the output of a cup or propeller generator as a result of brush wear).

The inspection of analogue traces will show faults as indicated by incorrect zero, stepped traces due to friction, noise (which may be evident at low wind speeds), low sensitivity (at low speeds), and irregular or reduced variability of recorded wind.

Instruments should be inspected for physical damage, by checking the zero of the anemometer system by holding the cups or propeller, and by checking vane orientation by holding it fixed in a predetermined position or positions. Repairs to the sensors are usually only practicable in a workshop.

System checks should regularly be carried out on the electrical and electronic components of electrical recording or telemetering instruments. Zero and range checks should be made on both the speed and direction systems.

ANNEX. THE EFFECTIVE ROUGHNESS LENGTH

For the purpose of exposure correction, a roughness length z_0 that represents the terrain over 2 km of upstream fetch is needed as a function of wind direction. The quality of the roughness correction is very much dependent on the accuracy of this roughness length.

Over sea, the task is relatively simple because of the uniform fetch. The so-called Charnock relation can be applied. It expresses the sea surface roughness to the friction velocity u^* and the gravitational acceleration g by means of $z_{0u} = \alpha\, u^{*2}/g$, where α is an empirical constant approximately equal to 0.014. The friction velocity relates to the neutral wind profile by means of $U(z) = (u^*/\kappa)\ \ln\,(z/z_{0u})$, where κ is the Von Karman constant (0.4) and z is the measurement height. These two equations have to be solved iteratively, which can be done by starting with $z_{0u} = 0.000\,1$, computing u^* from the log-profile, evaluating z_{0u} again, and repeating this a few times.

The surface roughness length over land depends on the surface cover and land use and is often difficult to estimate. A subjective way of determining z_{0u} is by a visual survey of the terrain around the wind station with the help of the table below, the validity of which has been recently corroborated (Davenport et al., 2000). Choosing wind direction sectors of 30° up to a distance of 2 km is most convenient. With very non-homogeneous fetch conditions, an effective roughness should be determined by averaging ln (z_{0u}) rather than z_{0u} itself.

The best way of determining z_{0u} is with the help of about one year of climatology of the standard deviations. The standard deviations of wind speed and wind direction are related to the upstream roughness over a few kilometres and can be used for an objective estimate of z_{0u}. Both the standard deviation of wind speed s_u and the standard deviation of wind direction s_d (in radians) can be employed by means of the following formulae:

$$s_u/U = c_u \kappa \left[\ln\left(z/z_{0u}\right)\right]^{-1} \tag{5.A.1}$$

$$s_d/U = c_v \kappa \left[\ln\left(z/z_{0u}\right)\right]^{-1} \tag{5.A.2}$$

where $c_u = 2.2$ and $c_v = 1.9$ and $\kappa = 0.4$ for unfiltered measurements of s_u and s_d. For the measuring systems described in section 5.8.3, the standard deviation of wind speed is filtered by about 12%, and that of wind direction by about 2%, which implies that c_u and c_v reduce to 1.94 and 1.86, respectively. In order to apply the above equations, it is necessary to select strong wind cases ($U > 4$ m s^{-1}) and to average s_u/U and/or s_d over all available data per wind sector class (30° wide) and per season (surface roughness depends, for example, on tree foliage). The values of z_{0u} can now be determined with the above equations, where comparison of the results from s_u and s_d give some idea of the accuracy obtained.

In cases where no standard deviation information is available, but the maximum gust is determined per wind speed averaging period (either 10 min or 1 h), the ratios of these maximum gusts to the averages in the same period (gust factors) can also be used to determine z_{0u} (Verkaik, 2000). Knowledge of system dynamics, namely, the response length of the sensor and the response time of the recording chain, is required for this approach.

Terrain classification from Davenport (1960) adapted by Wieringa (1980*b*) in terms of aerodynamic roughness length z_0

Class index	*Short terrain description*	z_0 *(m)*
1	Open sea, fetch at least 5 km	0.000 2
2	Mud flats, snow; no vegetation, no obstacles	0.005
3	Open flat terrain; grass, few isolated obstacles	0.03
4	Low crops; occasional large obstacles, $x/H > 20$	0.10
5	High crops; scattered obstacles, $15 < x/H < 20$	0.25
6	Parkland, bushes; numerous obstacles, $x/H \approx 10$	0.5
7	Regular large obstacle coverage (suburb, forest)	1.0
8	City centre with high- and low-rise buildings	≥ 2

Note: Here x is a typical upwind obstacle distance and H is the height of the corresponding major obstacles. For more detailed and updated terrain class descriptions see Davenport et al. (2000) (see also Part II, Chapter 9, Table 9.2).

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