

## CHAPTER 5 — MEASUREMENT OF SURFACE WIND

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## CHAPTER 5

### MEASUREMENT OF SURFACE WIND

#### 5.1 General

##### 5.1.1 Definitions

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.

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.

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

*Averaged quantities* are quantities (e.g. horizontal wind speed) that are averaged over a time period of 10 to 30 minutes. This chapter deals only with averages over 10-minute intervals (aeronautical applications might need shorter averaging intervals; see Chapter 2, Part II).

*Standard deviation* is  $\left\{ \overline{(s - \bar{s})^2} \right\}^{1/2}$  where  $s$  is a time-dependent signal (e.g. horizontal wind speed) and the overbar indicates time-averaging. The standard deviation is used to characterize the magnitude of the fluctuations in a particular signal.

*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 observe sharp peaks, which are called 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 observed 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 a further discussion).

*Time constant* (of a first-order system) is the time required for a device to detect and indicate about 63 per cent 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 per cent 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 that 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 wave length* is the passage of wind required by a vane without damping to go through one period of an oscillation.

##### 5.1.2 Units and scales

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

Wind direction should be reported in degrees to the nearest 10 degrees, using a 01 ... 36 code (e.g. code 2 means that the wind direction is between 15 and 25°), and should represent an average over 10 minutes (see Chapter 2, Part II for aeronautical purposes). Wind direction is defined as the direction from which the wind blows, and is measured clockwise from geographical north.

"Calm" should be reported when the average wind speed is less than 1 kn. 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 reported according to Code Table 0878 (the azimuth ring should be aligned with its zero coinciding with the Greenwich 0° meridian) found in the *Manual on Codes* (WMO, 1995).

##### 5.1.3 Meteorological requirements

Wind observations are required for weather monitoring and forecasting, for wind load climatology, for probability of wind damage and wind energy, and as part of the estimation of surface fluxes, e.g. evaporation for agricultural and for air pollution dispersion applications. Performance requirements are given in Chapter 1, Part I. An accuracy for horizontal speed of  $0.5 \text{ m s}^{-1}$  below  $5 \text{ m s}^{-1}$  and better than 10 per cent above  $5 \text{ m s}^{-1}$  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 observation 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 (see section 5.9).

Many applications need information about the gustiness of the wind. Such applications are nowcasting for aircraft take-off and landing, wind-load climatology, air pollution dispersion problems, and exposure correction. Two variables are suitable for routine observation, namely the standard deviation of wind speed and direction and the three-second 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 (the table below provides wind speed equivalents in common use for estimations).

The instruments and techniques specifically discussed are only a few of the more convenient ones available and do not comprise a complete list. The references 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 sensors are used to a lesser extent for routine observations but can perform satisfactorily, while those developed or currently in use as research tools may become practical for routine observations with advanced technology.

Examples are the pitot tube and the sonic anemometer. The pitot tube anemometer measures the pressure in a pressure tube that is kept aligned with the wind vector by means of a direction vane. It is relatively simple but has the disadvantage of a non-linear relation between wind speed and pressure, which is not convenient for averaging. The sonic anemometer measures the time between the emission and reception of an ultrasonic pulse travelling over a fixed distance. Although the principle works very well, it can be less reliable in rainy conditions when water on the sensor changes the length of the acoustic path.

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 by estimating the mean and extreme by reading the record.

**Wind speed equivalents**

<i>Beaufort scale number and description</i>	<i>Wind speed equivalent at a standard height of 10 metres above open flat ground</i>				<i>Specifications for estimating speed over land</i>
	<i>(kn)</i>	<i>(m s<sup>-1</sup>)</i>	<i>(km h<sup>-1</sup>)</i>	<i>(mi h<sup>-1</sup>)</i>	
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	

## 5.2 Estimation of wind

In the absence of equipment for measuring the wind, the observations must be made by estimation. Errors in observations made in this way may be large, but provided the observations are used with caution the method may be justified as providing data that would otherwise not be available at all.

### 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 table, will be found especially useful.

In order to make the estimates, the observer 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 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, etc. 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 due to buildings, etc. 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 make observations 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 observation should be made 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, then the observation point should be distant from obstructions by at least 10 times the height of the obstruction.

### 5.3.2 Wind direction

Direction may be estimated from a vane (weather cock) mounted on a pole which 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, then the direction of the wind 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 the 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. Near the starting threshold speed, however, substantial deviations from linearity can occur (see Moses, 1968 for design considerations).

Also, in such well-designed anemometers, the linearity of response is independent of air density, has good zero and range stability, and is easily reproduced in a manufacturing process.

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 most 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 per cent for some designs and 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, where it should be noted that propeller vanes have an advantage over cup anemometers because they have virtually no vertical component overspeeding.

Since both cup and propeller rotors turn with an angular velocity which 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 to advantage. The choice of signal generator or transducer depends largely on the type of data processor and readout 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 unreasonably.

The attainable and satisfactory characteristics for wind-speed sensors are:

Range:	0.5 to 75 m s <sup>-1</sup> (1 to 150 kn)
Linearity:	±0.5 m s <sup>-1</sup> (±1 kn)
Response length:	2 to 5 m.

### 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 and in case it is sufficiently well designed to have a single equilibrium position with respect to each wind direction.

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 good, as having not too much overshoot, and a reasonably fast response (Wieringa, 1967).

The signal generator is essentially a shaft-angle transducer, and many varieties have been employed. Potentiometers, alternating and direct current synchros, digital angle-encoder disks, 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 readout 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 diminish the damping ratio unreasonably.

The attainable and satisfactory characteristics for wind-direction vanes are:

Wind speed operating range:	0.75 to 50 m s <sup>-1</sup> (1 to 150 kn)
Linearity:	±2 to ±5°
Resolution:	3° (e.g. 7-bit angle encoder)
Undamped wavelength:	less than 10 m
Damping ratio:	0.3 to 0.7

### 5.6 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 readouts which are directly proportional to the components. 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 (i.e. pure component sensitivity) is difficult to attain. Sonic anemometers can have difficulties during rain with droplets in the measuring path, which makes them less suitable as all-weather instruments.

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.

### 5.7 Other wind sensors

Many physical principles can be used to measure wind speed and direction, all having their own merits and problems. Most systems have been developed for specific purposes, such as small-scale fluctuations and air pollution studies. A few of them are:

- Pressure tube anemometers (see Gold, 1936, for a description of the Dines anemometer);
- Hot-wire anemometers;
- Karman vortex devices;
- Remote sensing with sound (SODAR), light (LIDAR) or electromagnetic waves (RADAR).

These techniques are less common in routine meteorological networks and will not be discussed in this *Guide*. Details are provided in Fritschen and Gay (1979).

### 5.8 Methods of data processing

Signals from anemometer/vane combinations can be processed and averaged in many different ways. Before considering the aspects of the entire wind-measuring chain (including filtering, recording and, possibly, processing by computer), it is useful to discuss the problem of averaging. This *Guide* deals with the following output: 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 has three particular problems associated with it. The first is that the independent average of speed and direction overestimates the mean vector by a small amount (generally between one and four per cent (MacCready, 1966)), which can be easily corrected for winds above 2 m s<sup>-1</sup> when the standard deviation of wind direction is measured. The second difficulty is the discontinuity of the wind direction between 0 and 360°. This problem can be solved either by recording on a cylinder, by extending the recorder range to 540°, for example (an electronic device switches 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°. The third difficulty is that the response of a cup anemometer and vane cannot be matched, simply because the cup anemometer has first-order response and the vane has second-order response. This problem, however, is 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, the data reduction is simpler than in those cases where components have to be computed, and finally 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 devices, both mechanical and electrical. Perhaps the simplest example is a turn-counting register on a rotating cup anemometer commonly used to measure the passage of wind during a fixed-time interval. At the other end of the complexity spectrum, special-purpose digital processors can be used for this purpose. Such microprocessors replace much of the classical electronics and can easily calculate averages, peak gusts, and standard deviations.

If wind speed and direction are recorded as continuous graphs, an observer can estimate 10-minute averages fairly accurately from a pen recording. The recorded wind trace can also be used to read peak gusts. The observation of dials or meters gives a feel for the wind speed and its variability, but is subject to large errors when averages are needed. These devices are, therefore, less suitable when 10-minute averages are needed 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 lead to 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 arrive both at gusts that are compatible between stations and at accurate and reliable standard deviations.

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 climatology of extreme load on buildings and constructions. 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 three seconds accommodates most potential users. Gusts that persist for about three seconds 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 size and to expose them to the full load of a potentially damaging gust.

Optimization of filtering for measuring the standard deviation of the horizontal wind speed as well as for the observation of gusts with a duration of a few seconds leads to conflicting requirements for the filter variables. The standard deviation requires as little filtering as possible, whereas for the detection of peak gusts, the signal has to be smoothed over a few seconds. Because the gusts are most critical with regard to filtering, the filter variables are optimized for the gust observations. In practice, this means that low-pass filtering is necessary. In the next section, recommendations are made for wind-measuring systems with exact values for the filter variables. The filtering that is necessary for gust observations also reduces the standard deviation. The reduction is about 10 per cent and can easily be corrected, provided that the measuring chain is well documented and that all the filtering variables are known. It is better, however, to sample the unfiltered signal separately for the purpose of measuring an unbiased standard deviation.

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 one second. Higher sampling frequencies can be used but are not necessary. Apart from the wind vane inertial damping, any further filtering should be avoided for the wind direction. This means that the standard deviation of wind direction can be determined within two per cent with most wind vanes.

For an accurate measurement of peak gusts, it is desirable to sample the filtered wind signal every 0.25 second (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. Corrections for this effect are known.

The accurate measurement 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 seven-bit resolution is quite sufficient here because then a 5° unit for the standard deviation can still be measured with an accuracy of one per cent (WMO, 1987).

### 5.8.3 *Recommendations for the design of wind-measuring systems\**

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, a counting device that counts the pulses in intervals of 0.25 second, and a microprocessor that computes averages and standard deviation over 10-minute intervals on the basis of 0.25-second samples. The extreme has to be determined from 3-second averages, i.e. by averaging over the last 12 samples. This averaging has to be done every 0.25 second (i.e. overlapping 3-second averages every 0.25 second). The wind direction is measured with a vane that has an undamped wavelength of 5 m, a damping ratio of 0.3, and a seven-bit digital encoder that is sampled every second. Averages and standard deviations are computed over 10-minute intervals, where successive samples are checked for continuity. If two successive samples differ by more than 180°, then 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 is 10 m), the standard deviations of wind speed and wind direction are reduced by about seven and two per cent, respectively. The gust duration corresponding to the entire measuring chain (as defined in section 5.1.1) is about three seconds.

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 wave length 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 second and analogue-to-digital conversion every 0.25 second. 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 per cent and two per cent, respectively and the gust duration is about three seconds. 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 three seconds, unless the pen recorder responds more slowly than the first-order filter.

\* Recommended by the Commission for Instruments and Methods of Observation at its tenth session, 1989.

The signal-processing procedure, as described above, is in accordance with Recommendation 3 (CIMO-X) (WMO, 1991) 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 three seconds, provided that the wind signal has been averaged over three-second intervals (i.e. non-overlapping averaging intervals). The resulting gust duration is about five seconds and the reduction in standard deviation is 12 per cent (Beljaars, 1987; WMO, 1987).

## 5.9 Exposure of wind instruments

### 5.9.1 *General problems*

Due to the effects of friction, wind speed increases considerably with height. For this reason, a standard height has been defined for the exposure of wind instruments above open terrain. The corresponding shift of wind direction with height over open terrain is relatively small and can be ignored in surface wind observations.

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 to compute such corrections are becoming available. To improve the applicability of wind data, the 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 observations that are made 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 location or even an acceptable location for a wind station. The importance of optimizing the location can hardly be overstressed, although it is difficult to give universal guidelines. An optimum location is one where the observed wind is most representative for the wind over an area of at least a few kilometres, or can easily be corrected to make it representative. Two aspects are very important. Firstly, either the sensors should be kept away from local perturbations or the wind station should be moved in cases where new buildings arise nearby. Secondly, the local perturbations should be well documented (Wieringa, 1983). Simple calculation procedures exist nowadays to determine the effect of local

topography (Walmsley, Taylor and Keith, 1986) and the climatology of the gustiness observations can be used to determine exposure corrections for non-uniform vegetation or other obstructions.

Where a standard exposure is unobtainable, the anemometer might be installed at such a height that its indications are reasonably unaffected by local obstructions and represent as far as possible what 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 affected by placing the anemometer at a height exceeding 10 m by an amount depending on the extent, height, and distance of the obstructions; but it is impracticable to give any general rule for determining this, since local conditions differ so widely. Evans and Lee (1981) discuss the nature of the problem in urban areas. Wieringa (1980) shows that this method of anemometer height increase does not work well if local sheltering varies strongly with azimuth.

Special precautions must be taken to keep the wind equipment 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.

### 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. 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 water-line of the buoy. However, other sources of error are often more significant than those arising from different exposure heights (see WMO, 1981 for a review). 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 not 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 observations at 10 m. In spite of 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).

### 5.9.4 *Exposure correction*

Surface wind observations 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). Over sea, the surface is horizontally homogeneous but most anemometers are positioned on a ship or a platform in such a way that considerable flow distortion occurs. The latter problem is even more serious than the differences in observation height between various stations (WMO, 1981).

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 a tendency exists 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 observation height have to be removed.

The correction of wind observation for local exposure can be performed only with measurements of reasonable quality at reasonably exposed locations. 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, is important for local forecasts, but cannot be used as a regionally representative wind.

Although most of the exposure correction can be directly applied to the measurements, it is better to disseminate the uncorrected observations accompanied by separate correction information. Moreover, the correction for upstream roughness depends on the application and cannot be performed at observation time. The corrected wind speed  $U_c$  at a 10-m height can be expressed as follows:

$$U_c = U \cdot C_F \cdot C_T \cdot \frac{\ln(10/z_{ou})}{\ln(z/z_{ou})} \cdot \frac{\ln(60/z_{ou}) \ln(10/z_o)}{\ln(10/z_{ou}) \ln(60/z_o)}$$

where  $U$  is the observed wind speed at height  $z$  (usually 10 m),  $C_F$  is the flow distortion correction,  $C_T$  is the correction factor due to topographic effects,  $z_{ou}$  is the roughness length of the terrain upstream of the wind station, and  $z_o$  is roughness length in the application (e.g. a grid box value in a numerical forecast model). In this expression,  $z$ ,  $z_o$  and  $z_{ou}$  have to be specified in metres. The different correction terms represent:

- (a) Flow distortion: The correction factor  $C_F$  accounts for flow distortion, which is particularly important for anemometers on ships, drilling rigs, 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 on the basis of potential flow around simple configurations can also be applied (Wessels, 1984; Wyngaard, 1981). For many well-designed wind stations, flow distortion can be neglected ( $C_F = 1$ );

- (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 observed 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 for the area rather than for 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, Taylor and Keith, 1986). Such computations are fairly complicated but have 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. The computational task is also simplified by standard software that is becoming available;

- (c) Non-standard observation height: This effect is simply corrected by assuming a logarithmic profile combined with the roughness length  $z_{ou}$  of the upstream terrain. This correction does not usually apply to land stations but can be important for stations over sea. The stability corrections are relatively small here, which justify the logarithmic form of the correction;
- (d) Roughness effects: Upstream roughness effects as well as the effects of surface obstacles can be corrected by extrapolating the wind speed logarithmically to a height of 60 m with the station specific roughness length  $z_{ou}$  and by interpolating back to 10 m with the roughness length  $z_o$  necessary for the application. The roughness length  $z_{ou}$  should be representative for a 2-km fetch upwind of the wind station; the value usually depends on wind direction. The annex discusses the methods of estimating  $z_{ou}$ ;

By extrapolating up to 60 m, the resulting wind speed is more representative for a large area and less dependent on local terrain features. Two comments are appropriate here. Firstly, 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  $z_{ou}$  is representative and has proved to give satisfactory results (Wieringa, 1986). Secondly, the stability corrections in the wind profiles cannot be neglected over the height range from 10 to 60 m. The effect of stability is relatively small in the present formulation because the stability corrections in the extrapolation upwards and the interpolation downwards cancel out.

## 5.10 Calibration and maintenance

The fully effective 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.

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, bearing friction, 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.

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## ANNEX

## THE EFFECTIVE ROUGHNESS LENGTH

For the purpose of exposure correction, a roughness length that is representative of 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  $z_{ou} = \alpha u_*^2/g$ , where  $\alpha$  is an empirical constant approximately equal to 0.014. The friction velocity relates to the neutral wind profile by means of  $U(z) = (u_*/\kappa) \ln(z/z_{ou})$ , where  $\kappa$  is the Von Karman constant (0.4) and  $z$  is the observation height. These two equations have to be solved iteratively, which can be done by starting with  $z_{ou} = 0.0001$ , computing  $u_*$  from the log-profile, evaluating  $z_{ou}$  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  $z_{ou}$  is by a land survey of the terrain around the wind station with the help of the table opposite. Choosing wind direction sectors of  $30^\circ$  up to a distance of 2 km is most convenient. With very non-homogeneous fetch conditions, an effective roughness should be determined by averaging  $\ln(z_{ou})$  rather than  $z_{ou}$  itself.

The best way of determining  $z_{ou}$  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  $z_{ou}$ . Both the standard deviation of wind speed  $\sigma_u$  and the standard deviation of wind direction  $\sigma_\theta$  (in radians) can be employed by means of the following formulae:

$$\sigma_u/U = c_u \kappa \ln^{-1}(z/z_{ou}) \quad (1)$$

$$\sigma_\theta/U = c_v \kappa \ln^{-1}(z/z_{ou}) \quad (2)$$

where  $c_u = 2.2$  and  $c_v = 1.9$  and  $\kappa = 0.4$  for unfiltered measurements of  $\sigma_u$  and  $\sigma_\theta$ . For the measuring systems described in section 5.8.3, the standard deviation of wind speed is filtered by about 12 per cent and that of wind direction by about two per cent, 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 ( $U > 4 \text{ m s}^{-1}$ ) and to average  $\sigma_u/U$  and/or  $\sigma_\theta$  over all available data per wind sector class ( $30^\circ$  wide) and per season (surface roughness depends for example on tree foliage). The values of  $z_{ou}$  can now be determined with the above equations, where comparison of the results from  $\sigma_u$  and  $\sigma_\theta$  give some idea of the accuracy obtained.

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

Class	Short terrain description	$z_o$ (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, $xH > 20$	0.10
5	High crops; scattered obstacles, $15 < xH < 20$	0.25
6	Parkland, bushes; numerous obstacles, $xH \approx 10$	0.5
7	Regular large obstacle coverage (suburb, forest)	(1.0)
8	City centre with high- and low-rise buildings	??

NOTE: Here  $x$  is a typical upwind obstacle distance and  $H$  is the height of the corresponding major obstacles.