



# ESDU 85020

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## **Characteristics of atmospheric turbulence near the ground Part II: single point data for strong winds (neutral atmosphere)**

**Associated software: ESDUpac E0108  
(ESDU 01008)**

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## THE PREPARATION OF THIS DATA ITEM

The work on this particular Data Item was monitored and guided by the Wind Engineering Panel. This Panel, which took over the work on wind engineering previously monitored by the Fluid Mechanics Steering Group, first met in 1979 and now has the following membership:

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## CHARACTERISTICS OF ATMOSPHERIC TURBULENCE NEAR THE GROUND PART II: SINGLE POINT DATA FOR STRONG WINDS (NEUTRAL ATMOSPHERE)

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## CHARACTERISTICS OF ATMOSPHERIC TURBULENCE NEAR THE GROUND

### Part II: single point data for strong winds (neutral atmosphere)

#### 1. NOTATION AND UNITS

|                          |                                                                                                         | Units             |                    |
|--------------------------|---------------------------------------------------------------------------------------------------------|-------------------|--------------------|
|                          |                                                                                                         | SI                | British            |
| $d$                      | effective displacement height of zero-plane above ground due to surrounding obstacles (Section 3)       | m                 | ft                 |
| $c$                      | exponent in expression giving $k_L$                                                                     |                   |                    |
| $f$                      | Coriolis parameter ( $f = 2\Omega \sin \phi$ )                                                          | rad/s             | rad/s              |
| $h$                      | boundary layer height ( $h = u_*/(6f)$ )                                                                | m                 | ft                 |
| $I_i$                    | intensity of turbulence ( $I_i = \sigma_i/V_z$ )                                                        |                   |                    |
| $i$                      | general values of $u$ -, $v$ - or $w$ -component at point in space at time $t$ ( $i = u, v$ or $w$ )    | m/s               | ft/s               |
| $j$                      | number of roughness changes between site and upwind equilibrium conditions (see Sketch 8.1)             |                   |                    |
| $k_L$                    | factor accounting for variation of $^xL_u$ with $V_{10r}$ and $f$ (Figure 3b)                           |                   |                    |
| $^xL_u, ^xL_v, ^xL_w$    | length scales of turbulence in $x$ -direction relating to $u$ -, $v$ - and $w$ -components respectively | m                 | ft                 |
| $n$                      | frequency                                                                                               | Hz                | Hz                 |
| $n_i$                    | $^xL_i n / V_z$                                                                                         |                   |                    |
| $P_i$                    | cumulative probability that any value of $i$ will be less than a particular value, $i_p$                |                   |                    |
| $p_i$                    | probability density functions of $u$ -, $v$ - or $w$ -component                                         | s/m               | s/ft               |
| $S_{uu}, S_{vv}, S_{ww}$ | spectral density functions of $u$ , $v$ - and $w$ -components respectively ( $0 < n < \infty$ )         | m <sup>2</sup> /s | ft <sup>2</sup> /s |
| $T$                      | averaging time or response period of measuring instrument                                               | s                 | s                  |
| $T_0$                    | duration of sample or wind-speed record                                                                 | s                 | s                  |
| $t$                      | time                                                                                                    | s                 | s                  |

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|                      |                                                                                                                                             |                   |                      |
|----------------------|---------------------------------------------------------------------------------------------------------------------------------------------|-------------------|----------------------|
| $u_*$                | friction velocity [ $u_* = V_{10}/(2.5 \ln(10/z_0))$ ]                                                                                      | m/s               | ft/s                 |
| $u, v, w$            | fluctuating components of wind speed at time $t$ along $x$ -, $y$ - and $z$ -axes respectively                                              | m/s               | ft/s                 |
| $V_{10r}$            | reference hourly-mean wind speed at $z = 10$ m for terrain with $z_0 = 0.03$ m                                                              | m/s               | ft/s                 |
| $V_h$                | gradient wind speed at $z = h$                                                                                                              | m/s               | ft/s                 |
| $V_z$                | hourly-mean wind speed at height $z$                                                                                                        | m/s               | ft/s                 |
| $x$                  | distance of terrain roughness change upwind of site                                                                                         | m                 | ft                   |
| $x, y, z$            | system of rectangular Cartesian co-ordinates with $x$ -axis defined in direction of mean wind                                               | m                 | ft                   |
| $z$                  | height above zero plane (see Section 3)                                                                                                     | m                 | ft                   |
| $z_0$                | surface roughness parameter (see Section 3)                                                                                                 | m                 | ft                   |
| $z_b, z_t$           | height of inner and outer layers respectively of non-equilibrium boundary layer (see Sketch 8.1)                                            | m                 | ft                   |
| $\phi$               | angle of latitude at site                                                                                                                   | degree            | degree               |
| $\rho$               | air density                                                                                                                                 | kg/m <sup>3</sup> | slug/ft <sup>3</sup> |
| $\sigma_i$           | standard deviation of $i$ -component at height $z$ for $T \rightarrow 0$ and $T_0 \rightarrow \infty$ ; $\sigma_i = \overline{(i^2)}^{1/2}$ | m/s               | ft/s                 |
| $\sigma_i\{T, T_0\}$ | standard deviation of $i$ -component corresponding to finite $T$ and $T_0$                                                                  | m/s               | ft/s                 |
| $\tau$               | time lag                                                                                                                                    | s                 | s                    |
| $\tau_z$             | shear stress                                                                                                                                | kN/m <sup>2</sup> | lbf/ft <sup>2</sup>  |
| $\Omega$             | angular rotation of Earth ( $= 72.9 \times 10^{-6}$ rad/s)                                                                                  | rad/s             | rad/s                |

## Subscripts

|                               |                                                                                          |
|-------------------------------|------------------------------------------------------------------------------------------|
| $b$                           | relates to value at inner layer of atmospheric boundary layer (see Sketch 8.1)           |
| $j$                           | relates to value for upwind equilibrium conditions (upwind of $j^{th}$ roughness change) |
| $x$                           | relates to site value when roughness changes exist upwind (non-equilibrium conditions)   |
| A bar ( $\bar{\phantom{x}}$ ) | denotes time-averaged values                                                             |
| A prime ( $\prime$ )          | indicates value for $V_{10r} = 20$ m/s                                                   |

## 2. PURPOSE, SCOPE AND APPLICABILITY OF THIS ITEM

Turbulence data are required for engineering calculations of gust speeds (see ESDU 83045<sup>6</sup>) and mean and fluctuating loading. In particular, spectral densities are required as input data for methods used in assessing dynamic response.

The definition of the properties described in this Item and other background information are given in Reference 3. The purpose of this Item, which supersedes ESDU 74031, is to provide the statistical properties of turbulence in the atmospheric boundary layer at a single point in space. The properties of turbulence at two points in space are dealt with in Reference 4.

In this Item the properties considered are:

- (i) intensities and Reynolds stresses,
- (ii) probability densities,
- (iii) spectral densities and integral length scales of turbulence.

The statistical properties presented are derived from world-wide measurements in the atmospheric boundary layer and, within the uncertainties of the data, can be taken to apply for neutral atmosphere\* conditions which include strong winds ( $V_{10} > 10$  m/s).

The data are mainly based on measured values for homogeneous terrain (*e.g.* open country or forests) but some measurements are available for built-up areas and these indicate that, within the scatter of the data, the present model is applicable for heights greater than about 10 m above the general level of ground obstructions. When the upwind fetch of uniform terrain is less than about 30 km the effect of roughness changes should be considered (see Section 8).

For very hilly or mountainous terrain the spectral data in Section 6 do not apply. In such cases secondary peaks in the normalised spectra ( $nS_{ii}/\sigma_i^2$ ) may occur at low frequencies (see, for example, Derivation 27). Some additional data for complex terrain are provided in Derivation 44.

The principal difference between the data presented in this Item and previous data (for example in ESDU 74031 which this Item supersedes) is that this Item recognises that the characteristic properties of turbulence (variances and length scales) are dependent on wind speed (except in a layer close to ground level). The reason for this is that the present data are based on similarity theory which shows that as the reference wind speed increases, the boundary layer depth increases and the typical size and intensity of turbulence within the boundary layer are then scaled accordingly.

Sections 3 to 7 present the data for uniform terrain (equilibrium boundary layer) conditions. Section 8 provides guidance on the effect of step changes in terrain roughness upwind of the site. Section 9 discusses the uncertainty of the data. The Appendices contain the equations from which the graphical data are obtained and gives the background to their derivation and to the methods given in the main part of the Item.

The full methods on which this Data Item is based have been programmed into the software package, ESDUpac A9232, described in ESDU 92032<sup>10</sup>.

\* See Item 82026<sup>5</sup> for a further explanation of this term and its applicability to the strong wind condition.

## 3. INPUT DATA

A description of the atmospheric boundary layer and the mechanisms producing turbulence are contained in Item 74030<sup>3</sup>. The main factors that affect turbulence in the neutral atmospheric boundary layer (and hence the parameters that are required as input data when using this Item) are:

- (i) surface roughness parameter,  $z_0$ , see Table 3.1,
- (ii) the height above the zero plane (see following),
- (iii) hourly-mean reference wind speed ( $V_{10r}$ ) and the local hourly-mean wind speed.

The relationship between  $V_{10r}$  and  $V_{10}$  and the variation of mean wind speed,  $V_z$ , with height and terrain roughness (including terrain with roughness changes) is dealt with in ESDU 82026<sup>5</sup> and 84011<sup>7</sup> and the user should refer to those documents for data appropriate to strong-wind or neutral atmosphere conditions, or, preferably, use the computer program ESDUpac A9232 described in ESDU 92032<sup>10</sup>.

The height,  $z$ , at which the properties are presented is measured from the zero-plane displacement height,  $d$ , above the ground, so that height above ground is given by  $(z + d)$ . Approximate values of  $d$  are given in Table 3.1 based on the assumption that the zero-plane is about one or two metres below the general height of the surrounding buildings or trees. For more detailed information see ESDU 82026<sup>5</sup>.

**TABLE 3.1 Typical Values of Terrain Parameters  $z_0$  and  $d$**

| Terrain Description                                                                                                                    | $z_0$ (m) | $d$ (m)  |
|----------------------------------------------------------------------------------------------------------------------------------------|-----------|----------|
| City centres<br>Forests                                                                                                                | 0.7       | 15 to 25 |
| Small towns<br>Suburbs of large towns and cities<br>Wooded country (many trees)                                                        | 0.3       | 5 to 10  |
| Outskirts of small towns<br>Villages<br>Countryside with many hedges, some trees and some buildings                                    | 0.1       | 0 to 2   |
| Open level country with few trees and hedges and isolated buildings;<br>typical farmland                                               | 0.03      | 0        |
| Fairly level grass plains with isolated trees                                                                                          | 0.01      | 0        |
| Very rough sea in extreme storms (once in 50-yr extreme)<br>Flat areas with short grass and no obstructions<br>Runway area of airports | 0.003     | 0        |
| Rough sea in annual extreme storms<br>Snow covered farmland<br>Flat desert or arid areas<br>Inland lakes in extreme storms             | 0.001     | 0        |

## 4. TURBULENCE INTENSITIES AND REYNOLDS STRESSES

### 4.1 Turbulence Intensity: $u$ -component

Turbulence intensity is a measure of the magnitude of the fluctuating velocity component compared to the hourly-mean wind speed at the same height. It is a non-dimensional quantity derived from the variance ( $\sigma_i^2$ ) and for the  $u$ -component is  $I_u = \sigma_u/V_z$ .

For the situation where the terrain is uniform upwind of the site for at least 30 km (*i.e.* the atmospheric boundary layer is in dynamic equilibrium with the underlying surface) values of  $I_u$  are given by Equations (4.1) to (4.3). The derivation of these data is summarised in Item 83045 and a simplified presentation is given in Figure 1. Figure 1a provides values of  $I_u'$  when the reference wind speed ( $V_{10r}$ ) is 20 m/s. Figure 1b gives a correction factor by which  $I_u'$  must be multiplied when  $V_{10r} \neq 20$  m/s.

$$I_u = \frac{\sigma_u}{u_*} \frac{u_*}{V_z} \quad (4.1)$$

where

$$\frac{\sigma_u}{u_*} = \frac{7.5\eta[0.538 + 0.09 \ln(z/z_0)]^p}{1 + 0.156 \ln(u_*/(fz_0))} \quad (4.2)$$

$$\eta = 1 - 6fz/u_*; \quad p = \eta^{16}$$

and

$$V_z/u_* = 2.5[\ln(z/z_0) + 34.5fz/u_*]. \quad (4.3)$$

For the situation where there are roughness changes upwind of the site within  $x = 30$  km the local intensity of turbulence,  $I_{ux}$ , will deviate from the equilibrium value increasingly as  $x$  decreases. A simplified method for estimating  $I_{ux}$ , for a site with up to two step changes in terrain roughness upwind, is provided in Item 84030<sup>8</sup>. The results are presented in tabular form and approximate correction factors for hilly terrain are also provided. Item 92032<sup>10</sup> also contains a computer program to evaluate  $I_{ux}$  for flat or hilly terrain.

### 4.2 Turbulence Intensities: $v$ - and $w$ -components

Data from sources where both  $\sigma_u$  and  $\sigma_v$ , or  $\sigma_u$  and  $\sigma_w$ , have been measured simultaneously for neutral atmospheric conditions indicate that near the ground the ratios  $\sigma_v/\sigma_u$  and  $\sigma_w/\sigma_u$  are essentially constant irrespective of the nature of the terrain. Thus, values of  $I_v$  and  $I_w$  (and  $I_{vx}$  and  $I_{wx}$ ) can be obtained by evaluating  $I_u$  (or  $I_{ux}$  if roughness changes are to be considered) for the site in question and then multiplying this value by the ratio  $\sigma_v/\sigma_u$  or  $\sigma_w/\sigma_u$  (Figure 2). These are represented by

$$\frac{\sigma_v}{\sigma_u} = 1 - 0.22 \cos^4\left(\frac{\pi z}{2h}\right) \quad (4.4)$$

and

$$\frac{\sigma_w}{\sigma_u} = 1 - 0.45 \cos^4\left(\frac{\pi z}{2h}\right) \quad (4.5)$$

where  $h$  can be taken as  $u_*/(6f)$ .

This procedure assumes that the effect of any upwind roughness changes on  $\sigma_v$  and  $\sigma_w$  can be accounted for, to a first approximation, through the effect on the  $u$ -component. At large heights above the ground, as  $z \rightarrow h$ ,  $\sigma_v/\sigma_u$ , and  $\sigma_w/\sigma_u$  both tend to unity.

## 4.3 Reynolds Stresses

Retarding forces exerted on the wind at the surface of the Earth are transmitted upwards through the atmospheric boundary layer by shear forces, called Reynolds stresses, and also by the exchange of momentum, due to the movement of air. In applications to wind loading on ground-based structures knowledge of the Reynolds stresses is only required in special cases.

The Reynolds stresses are obtained from the co-variances  $\overline{uv}$ ,  $\overline{vw}$  and  $\overline{uw}$  and are zero for isotropic\* turbulence. Near the ground surface friction distorts the symmetry of turbulence and non-isotropic conditions result. However, in practice, the co-variances  $\overline{uv}$  and  $\overline{vw}$  are small and can be ignored but this is not so for the  $\overline{uw}$  co-variance.

The co-variance  $\overline{uw}$  is defined by the shear stress,

$$\tau_z = -\rho \overline{uw} = \rho u_*^2 (1 - z/h)^2. \quad (4.6)$$

Thus for heights up to about 300 m

$$\frac{-\overline{uw}}{\sigma_u \sigma_w} \approx \frac{u_*^2 (1 - 2z/h)}{\sigma_u (\sigma_w/\sigma_u) \sigma_u} = \frac{1 - 2z/h}{(\sigma_u/u_*)^2 (\sigma_w/\sigma_u)} \quad (4.7)$$

where, for an equilibrium boundary layer,  $\sigma_u/u_*$  is given by Equation (4.2) and  $\sigma_w/\sigma_u \approx 0.55$  (Figure 2).

Reported values of  $-\overline{uw}/(\sigma_u/\sigma_w)$  in the literature tend to be slightly higher than values given by Equation (4.7). The probable reason is the response characteristics of typical anemometers used to measure the vertical component of wind speed.

\* For isotropic turbulence the statistical properties do not change when the reference co-ordinates are rotated, i.e., the properties are independent of direction in the turbulence field.

## 5. PROBABILITY DENSITY

This property describes how the magnitudes of the fluctuating velocity components are distributed. A common assumption, which is reasonable in many applications, is that atmospheric turbulence is a ‘normal’ or Gaussian process with a probability density function for which

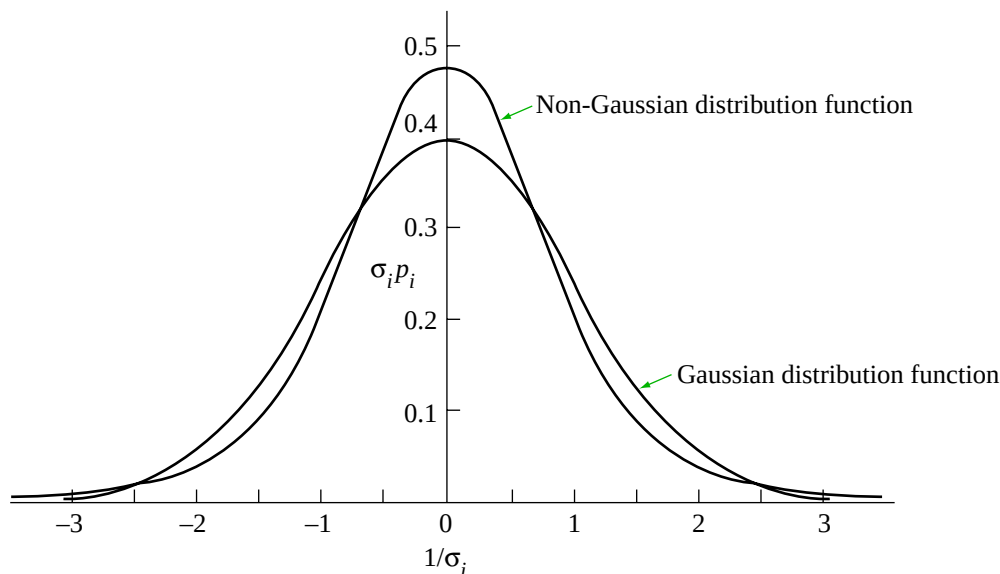
$$p_i = \frac{1}{\sigma_i(2\pi)^{1/2}} \exp[-i^2/2\sigma_i^2] \quad (5.1)$$

where  $i = u, v$  or  $w$ . The integral

$$P_i = \int_{-\infty}^{i_p} p_i di \quad (5.2)$$

gives the proportion of all values which can be expected to have values below a particular value  $i_p$ .

In practice, atmospheric turbulence contains “patches” of a significantly non-Gaussian nature (particularly in the lower 30 m) when larger gusts and longer lulls may occur more frequently than indicated by the Gaussian distribution, as illustrated in Sketch 5.1.



**Sketch 5.1 Probability density function**

For the calculation of wind loads on, and the response of, buildings in strong winds it is generally satisfactory in most applications to assume that the probability distribution is Gaussian. In the calculation or simulation of aircraft response to atmospheric turbulence this is not necessarily so and there have been several attempts to develop non-Gaussian models that are applicable to the “patches” mentioned earlier. One method is to generate a non-Gaussian random process by the multiplication of two Gaussian processes (see Reference 1). An alternative is to represent wind fluctuations as a statistical aggregate of “discrete gusts” (see Reference 2).

## 6. SPECTRAL DENSITY (UNIFORM TERRAIN)

As explained more fully in Reference 3, the variance ( $\sigma_i^2$ ) of a fluctuating component is made up from contributions over a range of frequencies; the spectral density property describes this frequency distribution and is particularly important in assessing dynamic effects induced by the wind at or near a natural frequency of a structure.

Considerable numbers of measurements of the spectra of gust velocities in the near-neutral atmosphere, or strong wind condition, at varying heights and for different terrains are available. Many of these show wide variations from each other when plotted in normalised form (e.g.  $nS_{ii}/\sigma_i^2$  against  $\ln n$ ), particularly in the low frequency region.

It is possible to attribute some of these variations to non-equilibrium boundary layer effects due to changes in terrain roughness upwind of, and close to, the measuring site and also to measuring and processing techniques. Methods of allowing for the effects of non-uniform terrain are given in Section 8. Also non-stationarity of the wind velocity measurements (when, in particular, the mean wind speed over successive intervals is varying with time) affects the form of the spectrum. However, the assumption of stationarity should lead to conservative loadings on conventional structures.

In most practical applications only spectral densities in the high frequency region are required and in this situation the data formulation can be considerably simplified. For simplicity of use, only the high frequency spectral data are given in Section 6.1. The forms of spectral equation applicable over the complete frequency range currently in use (e.g. the von Karman form) are not entirely satisfactory in representing measured data for all frequencies and heights in the atmospheric boundary layer. A modified von Karman model for spectral densities over the whole frequency range, together with the corresponding autocorrelation functions, is presented in Appendix B and is compatible with the high frequency data in Section 6.1.

### 6.1 Longitudinal $u$ -component: High Frequency Range ( $nz/V_z > 0.1$ )

The von Karman spectral equations (Equations (A2.1) and (A2.2) in Appendix A) have been generally accepted as the best analytical representation of isotropic turbulence over the whole frequency range. The effect of departure from isotropic turbulence near the ground can be allowed for by the variation with height and surface roughness of the appropriate variance  $\sigma_i^2$  and length scale parameter  $^xL_i$  since they typify the intensity and size of eddies constituting turbulence. However, high quality measurements of the autocorrelation ( $\rho_{ii}$ ) and spectral density ( $S_{ii}$ ) functions have shown that the integral length scale parameter, as given by

$$^xL_i = V_z \int_0^\infty \rho_{ii} d\tau, \quad (6.1)$$

when used in the von Karman spectral equation gives underestimates of spectral density in the high frequency region. The von Karman equation is therefore inadequate in representing all the characteristic properties of turbulence although it reduces to the correct functional form in the high frequency range ( $nz/V_z > 0.1$ ) when

$$\frac{nS_{uu}}{\sigma_u^2} = A \left( \frac{^xL_u n}{V_z} \right)^{-2/3}. \quad (6.2)$$

In order to ensure that the integral length scale given by Equation (6.1) can be used directly in Equation (6.2)

to predict  $S_{uu}$ , it can be established (see Section A2.1 of Appendix A) that the parameter  $A$  is given by

$$A = 0.115 [1 + 0.3151(1 - z/h)^6]^{2/3} \quad (6.3)$$

and takes the von Karman value of 0.115 for large heights but increases to a value of 0.142 close to the ground. For values of  $^xL_u$ , see Section 7.1.

## 6.2 Lateral v- and w-components: High Frequency Range ( $nz/V_z > 0.1$ )

For the v- and w-components, corresponding expressions for the spectral density in the high frequency range are given by

$$\frac{S_{vv}}{S_{uu}} = \frac{S_{ww}}{S_{uu}} = \frac{4}{3} \quad (6.4)$$

which is compatible with the von Karman expression in the high frequency range when the assumption of local isotropy is valid ( $^xL_v = ^xL_w = \frac{1}{2} ^xL_u$ ).