Effect of averaging times on turbulence intensity

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Introduction

- IEC 61400-12-1:2022 on power performance measurements:
  - 10' averages for large wind turbines
  - 1' averages for small wind turbines (annex H)
- IEC 61400-2:2013
  - Turbulence quantification uses measurements at 10' averages: *the average turbulence intensity at 15 m/s shall be reported. This turbulence intensity is the average turbulence intensity of all data points with 10-min average wind speeds between 14.5 m/s and 15.5 m/s*

Questions

- Should TI be reported at 1' or 10' averages? Does it matter?
- Does it make sense to stick to I_{15}?

Shorter averaging times

- Power performance measurements under IEC 61400-2:2013 annex H assumes 1' averages
- But IEC 61400-2:2013 Sect. 13.4 on duration testing requires 10' in each velocity bin between $2.2\,V_{\mathrm{av}}$ and 15 m/s with 10' averages.
- Within MT-2 there is strong support for 1' averages. Strongest support probably from industry. The rationale, as I understand it, is that 1' averages allow for a significantly shorter duration testing, as you need to fill the bins
- The same Section of IEC 61400-2:2013 also requires the turbulence intensity at 15 m/s (I_{15}) to be reported, using 10' averages. Should this also be changed to 1' averages?

Shorter averaging times (cont.)

The spectral gap

- The spectrum most frequently shown to illustrate the presence of a spectral gap is that by Van der Hoven (1957).

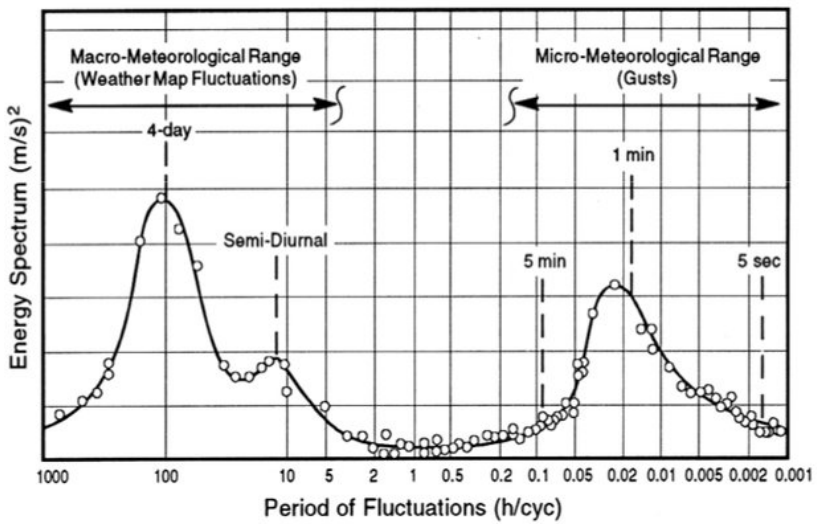


Figure: Van der Hoven spectrum (frequency-weighted power spectral density) with spectral gap

The spectral gap (cont.)

- Spectral gap shows neat separation between a deterministic part, fundamentally driven by earths orbit and rotation and a turbulent part
- Points to appropriate time scale for defining averages:
  - there is little power over time scales between say 3h and 20 min
  - and so the mean is quite independent of the exact length of the averaging interval
  - (sampling is statistically stationary)

Problem with the spectral gap

- Many authors have noted that the spectral gap does not always occur
- In the van der Hoven spectrum, 1' is obviously not in the spectral gap

Illustrative spectra

Data

- From our catalogue of turbulence data, we gathered 4 datasets with sampling frequencies of 1 to 10 Hz
- There are more, but we started with the datasets that were clean

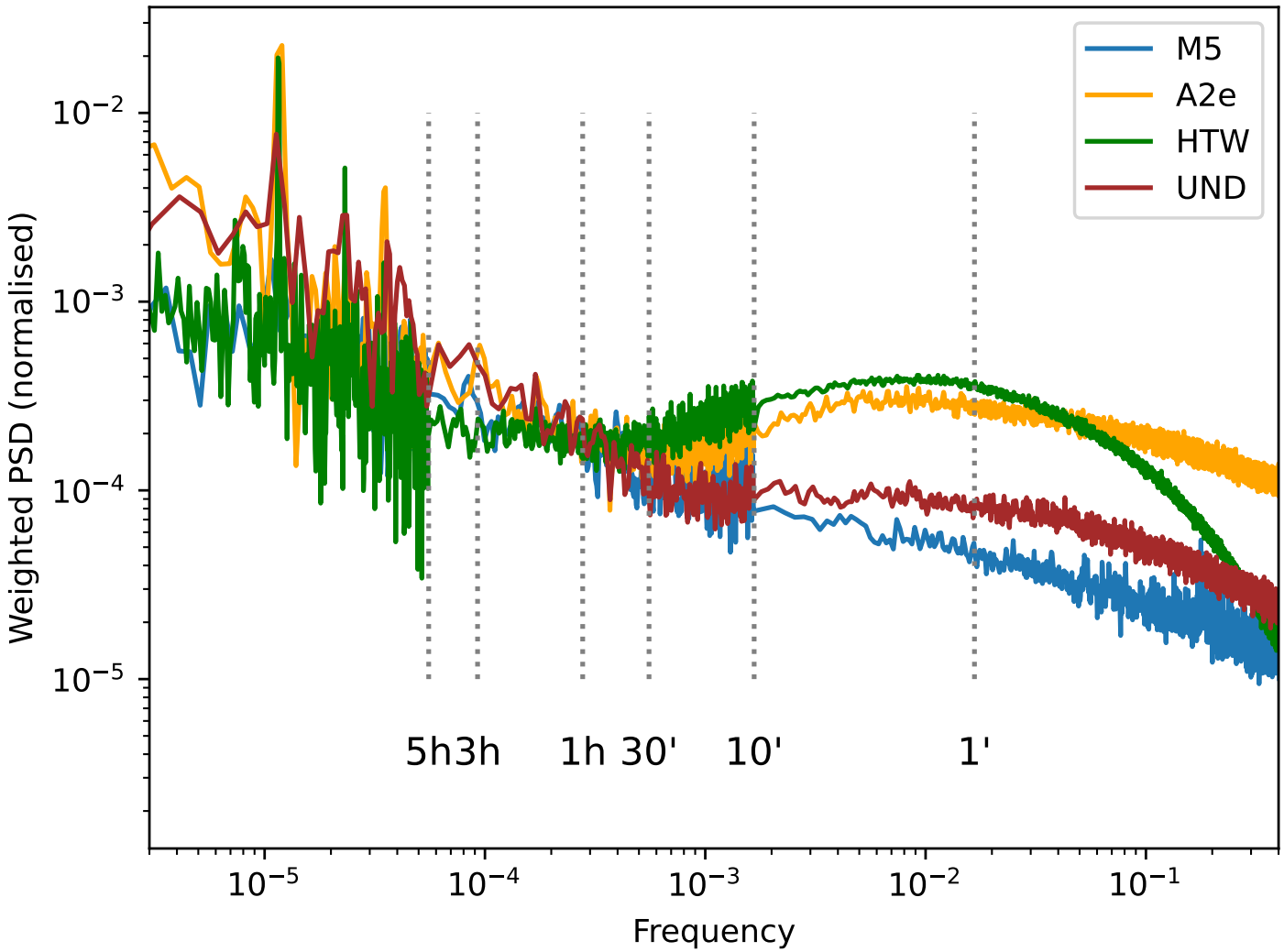
Site descriptions

- HTW
  - Rooftop (Berlin)
  - 3D-Sonic and cup anemometers
  - Sonic sampling frequency: 1 Hz
- A2e
  - Washington and Oregon Columbia Basin
  - $h = 10$ m
  - Sonic anemometer
  - Sampling frequency: 20 Hz
- M5
  - NREL M5 Tower
  - $h = 135$ m
  - Sampling frequency: 20 Hz

Site descriptions (cont.)

- UND
  - Surface Meteorological Station at the University of North Dakota (UND)
  - $h = 21$ m
  - 3D sonic anemometer
  - Sampling frequency: 20 Hz

Spectra

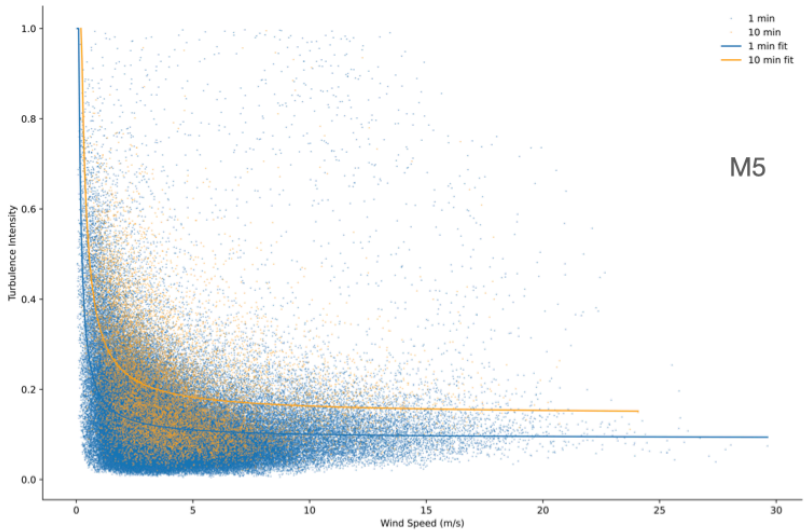

M5
A2e
HTW
UND
Weighted PSD (normalised)
10^{-2}
10^{-3}
10^{-4}
10^{-5}
5h
3h
1h 30'
10'
1'
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
Frequency

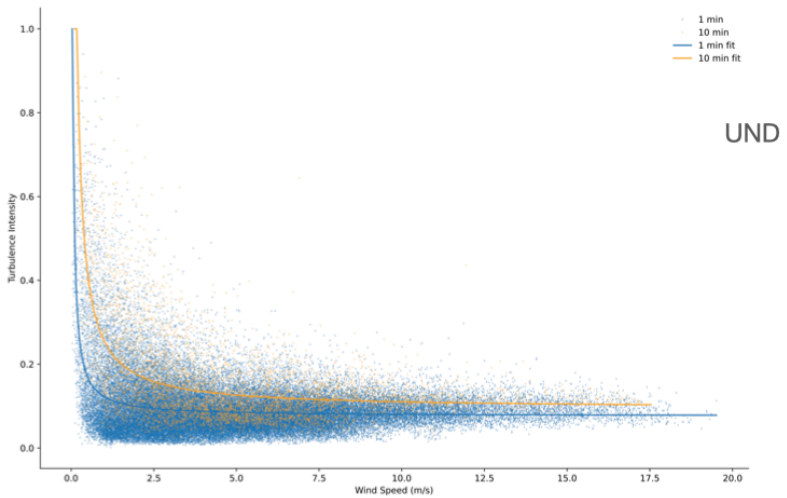
Spectra (cont.)

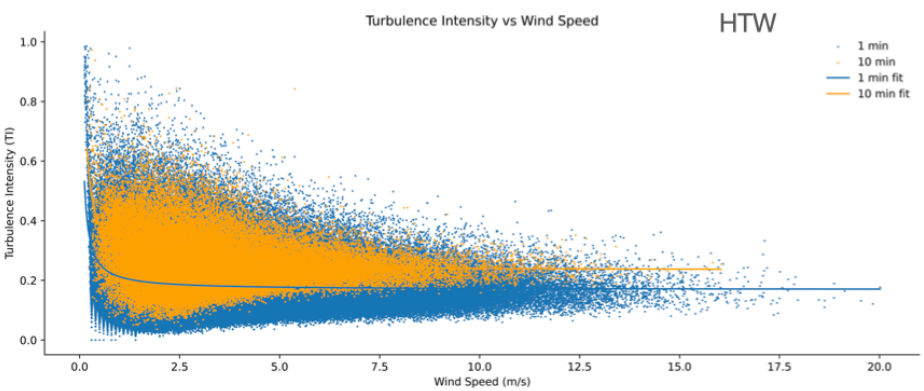
Figure: Frequency weight power spectral densities, normalised for comparability

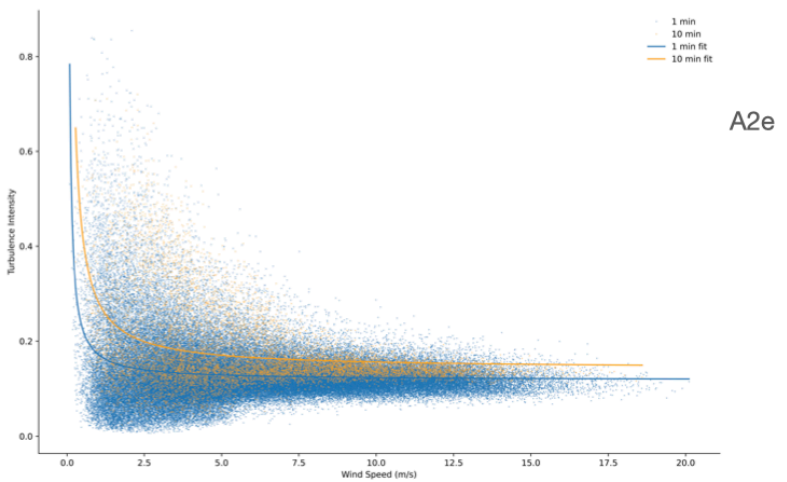
TI plots

TI plots (cont.)









Effect of averaging

	1 min			10 min			Difference		
Site	I_5	I_10	I_15	I_5	I_10	I_15	Δ I_5	Δ I_10	Δ I_15
HTW	18%	17%	17%	26%	24%	23%	8%	7%	6%
M5	10%	12%	14%	18%	19%	21%	8%	7%	7%
A2e	13%	12%	12%	18%	14%	14%	5%	2%	2%
UND	8%	9%	9%	11%	12%	11%	3%	3%	2%

- TI for 1' averaging systematically lower than for 10'
- Agrees with previous reports ([Goit et al 2021, Infield et al 2014]) and understandable from first principles
- Two sites with largest effect of averaging on TI are extremely different: HTW rooftop and M5 tall met mast
- This suggests that it may be hard to predict effect of averaging window on TI from site conditions.

Effect of averaging (cont.)

- Not so easy to predict from spectra when the effect will be large.
- Two sites (HTW and A2e) have a very prominent bump around 1', but does not seem to predict very well the effect of averaging times terrain).
- With some good will, the effect of a range of averaging times matches with the spectral trend

Effect of averaging (cont.)

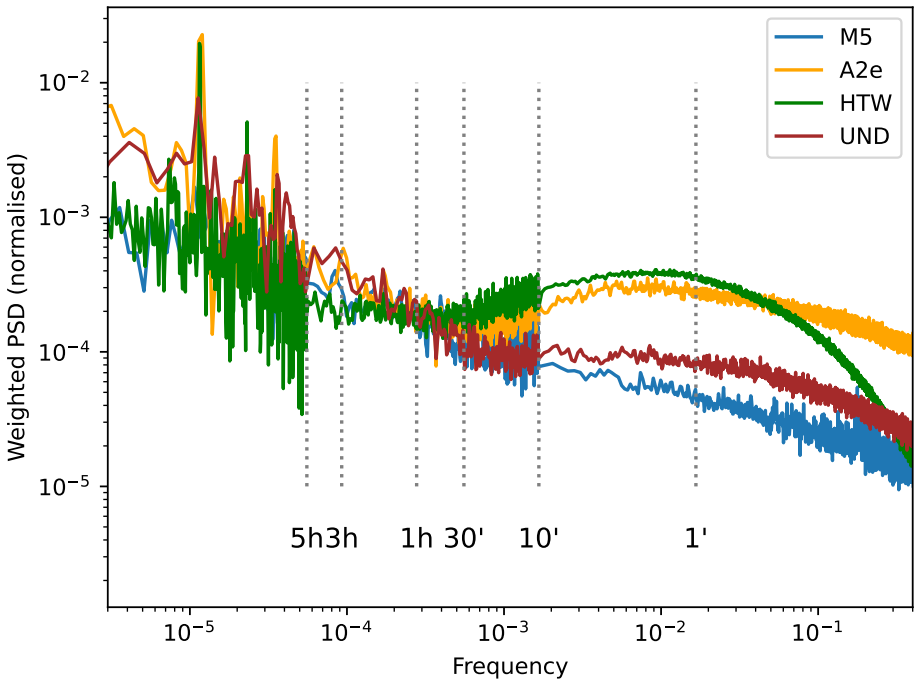


Figure: Spectra

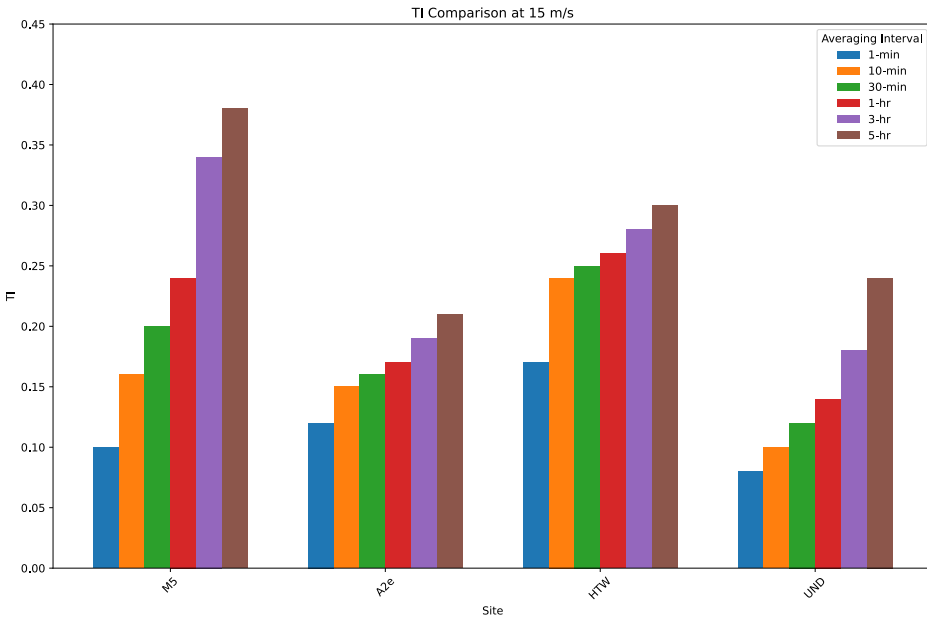


Figure: Effect of averaging on I_{15}

Relation between TI at different averaging times

- 61400-2:2013:

$$\sigma_{10}^2 = \frac{1}{10}\sum_{i}^{10}\left(\sigma_{1,i}^2 + \mu_{1,i}^2\right) - \mu_{10}^2 \tag{1}$$

which with a bit of maths can be rewritten as

$$\sigma_{10}^2 = \frac{1}{10}\sum_{i=1}^{10}\sigma_{1,i}^2 + \frac{1}{10}\sum_{i=1}^{10}\left(\mu_{1,i} - \mu_{10}\right)^2 \tag{2}$$

where the first term presents the variance with the samples and the second one the variance between the samples. The second term is small when the 1' averages differ little from the underlying 10' averages.

Suggestion

- TI at 10' averaging time is the more conservative metric.
- It is also used for large wind turbines. IEC 61400-2 will include medium wind turbines (RSA up to 1200m^2). It would be wise to be consistent
- Even if duration tests move to 1' averages the TI reported should be the one for 10' averages. This can be obtained from the previously presented equations, one of which is already included in the present standard

Turbulence at 15 m/s

- Is I_{15}, the value of turbulence intensity at 15 m/s the most meaningful value for distributed / small wind?

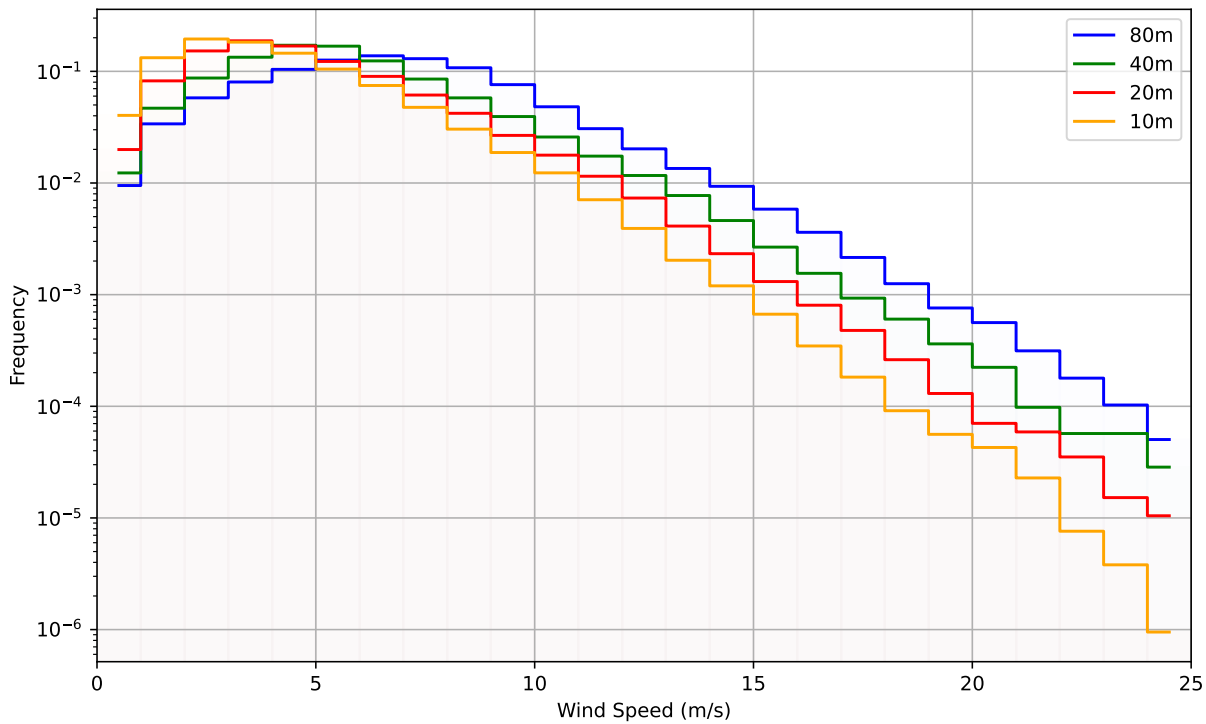


Figure: Wind speed histograms for 10' averages at different heights (site: Cabauw, Netherlands)

Turbulence at 15 m/s (cont.)

- Task 27 already recommended using a lower reference wind speed.
- Differences between I_{10} and I_{15} are relatively small The function expressing TI(V) is quite flat between 10 and 15 m/s (see **??**). Therefore reported values for I_{10} would not be very different from I_{15} Should we argue for this in MT-2?