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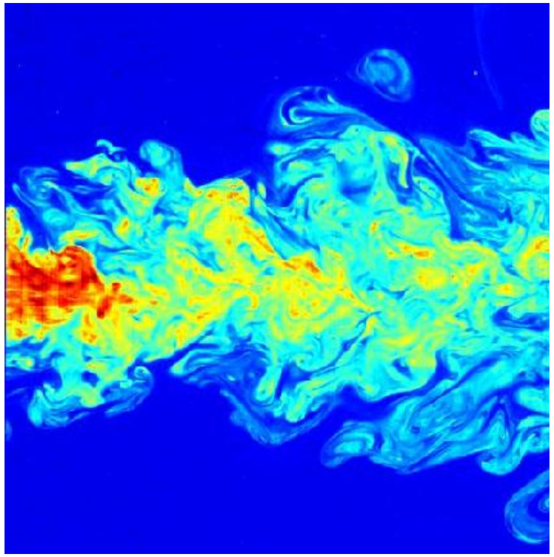
An evaluation of Turbulence Intensity as measured by AQ510 and other measurement techniques.

SWECO

WHAT IS TURBULENCE?

Atmospheric turbulence is random and constantly changing motion of air within the wind's overall average motion.



Causes of atmospheric turbulence:

Friction between moving air and terrain.
Solar heating during the day (convection).
Interaction of air flows with differing velocities.
Interaction of air flows with differing directions.
Friction effects from structures.

Daily Cycle:

The daily cycle is due to a strong relationship between turbulence and atmospheric stability. During stable conditions at night turbulence tends to be low. During the day turbulence tends to be high due to mixing caused by solar heating effects.

WHAT IS TURBULENCE INTENSITY?

In the wind energy industry, turbulence is quantified with a metric called Turbulence Intensity (TI) – the standard deviation of the horizontal wind speed divided by the average wind speed over the same time period, typically 10 minutes. If the wind fluctuates rapidly, then the turbulence intensity will be high. Conversely, steady winds have a lower turbulence intensity. Typical values of horizontal turbulence intensity, measured with a cup anemometer, range from 3% to 20%. - *Julie Lundquist, North American Windpower, September 2012*

$$\mathbf{TI = u'/U}$$

u' = the Root-Mean-Square (RMS), or Standard Deviation, of the turbulent velocity fluctuations at a particular location over a specified period of time.

U = the average of the velocity at the same location over same time period.

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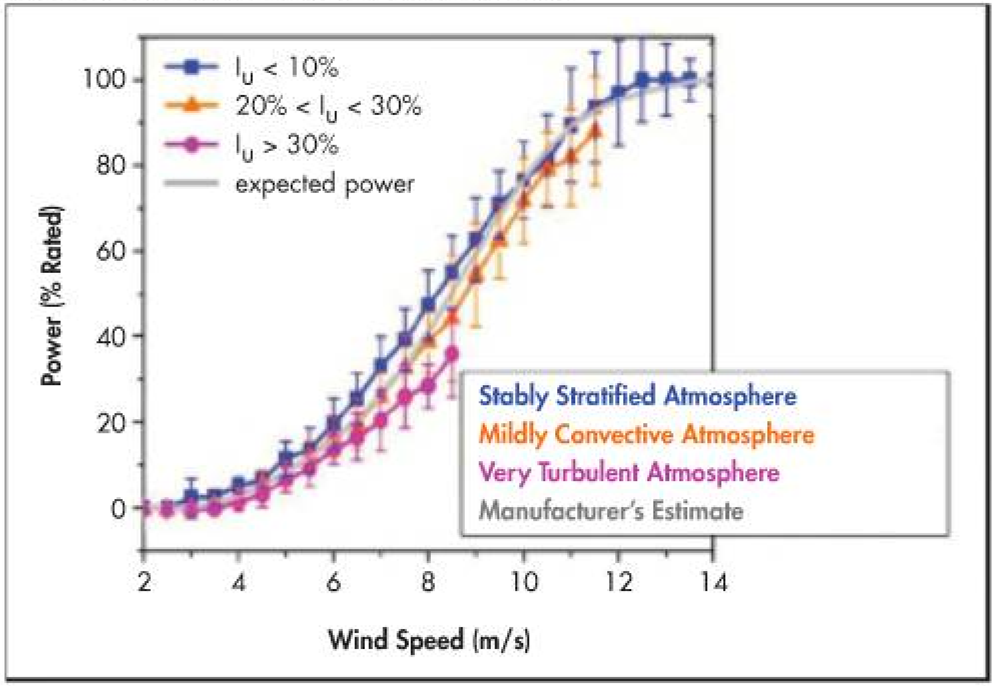
WHY IS TI IMPORTANT?

Atmospheric turbulence impacts wind energy in several ways, specifically through power performance effects, impacts on turbine loads, fatigue, wake effects, and noise propagation.

Variation in turbulence can impact turbine power curve.
Turbulence can affect turbine loading and lifespan.
Turbulence can affect noise propagation and distribution.

Figure 2: Power Curve Variability with Turbulence Intensity



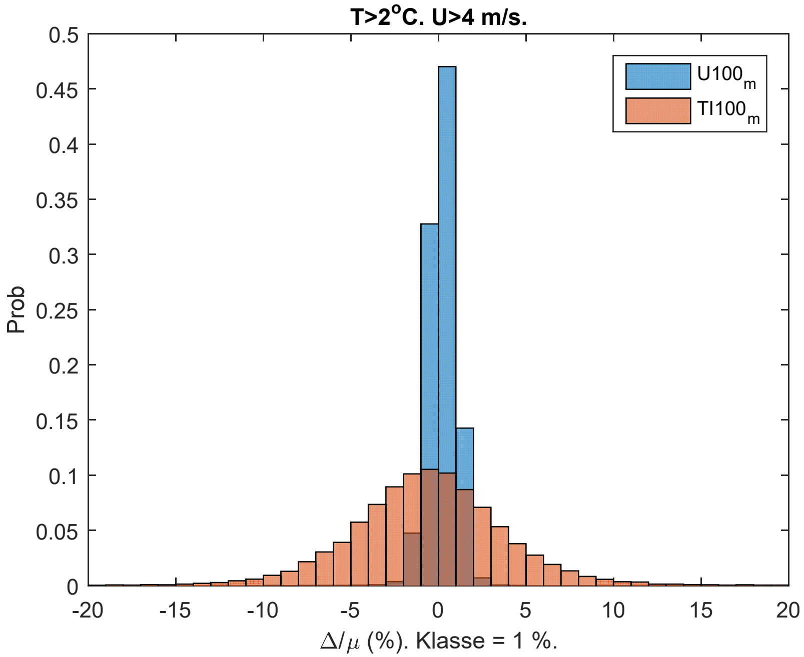
Source: American Meteorological Society

Power production at wind speeds of around 8m/s can vary by up to 20% depending upon TI!

Example 1 – 2 Anems at same height

- Two (2) Thies first class anemometers at same height.
- Difference between anemometers divided by average to show relative (%) difference.
  Bin Size = 1%
- We see the distributions of wind speed (WS) and turbulence intensity (TI)
- Both anemometers are good. There is no error. Difference is caused by naturally random process – WIND
- Turbulence varies much more than WS. TI has a larger spread.

Difference between 2x Thies FC at same height



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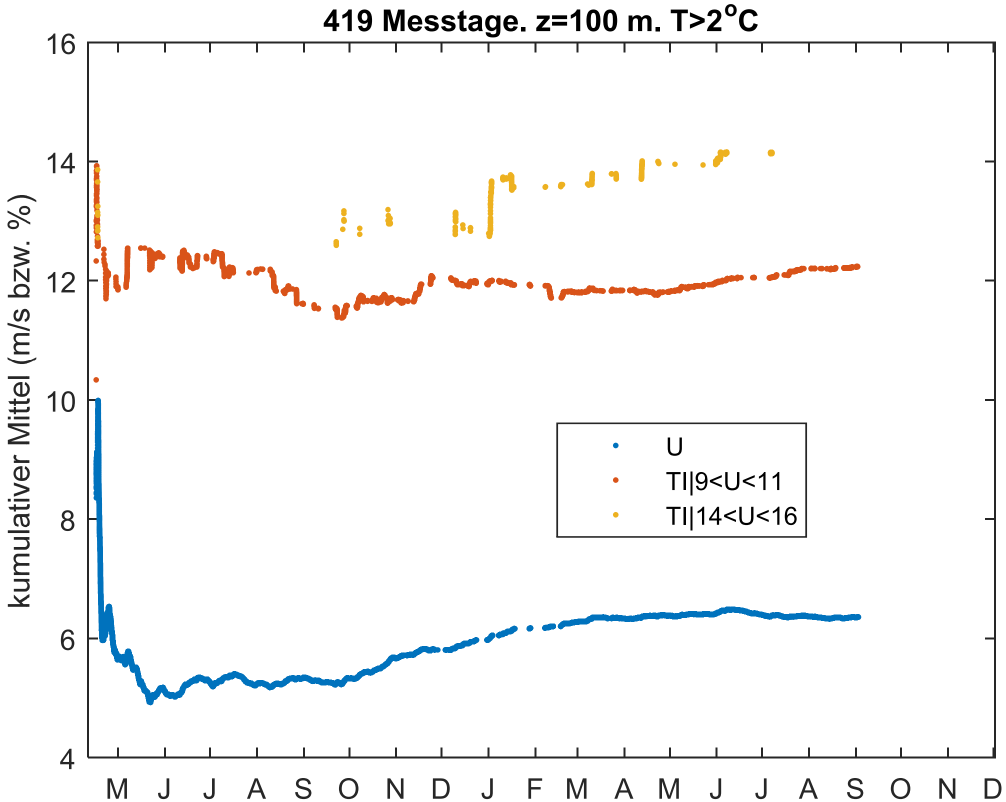
TI How long to measure?

- How long should we measure?
- Cumulative average is a useful tool to assess this.
- Graph shows 17 months with time on x-axis and cumulative mean on y-axis.
- Based upon statistical law of large numbers the curve approaches the “true” average.
- 1 year fluctuations of BLUE curve (WS) are in the percentage range.
- BROWN curve shows TI(%) in WS interval 9<U<11 m/s.
- Deviations get smaller with time and converge to about 12 % after one year.



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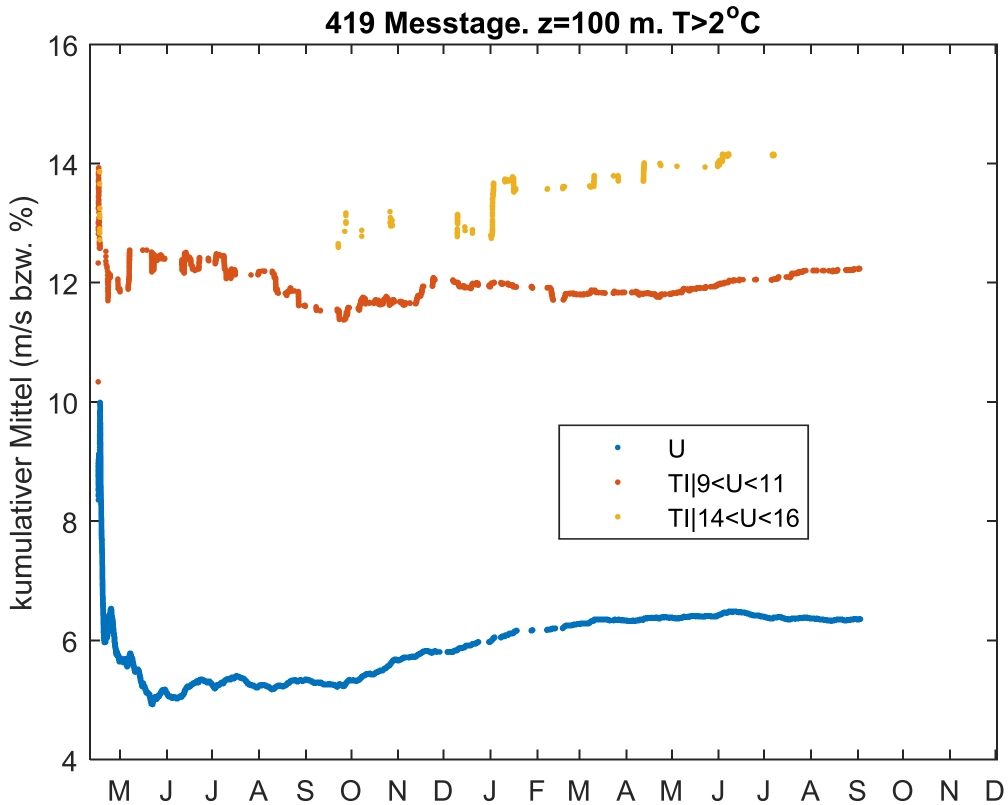
TI Wind Speed Range & Data availability

- The Yellow curve shows TI for stronger WS interval 14<U<16 m/s. Which is relatively rare on this site.

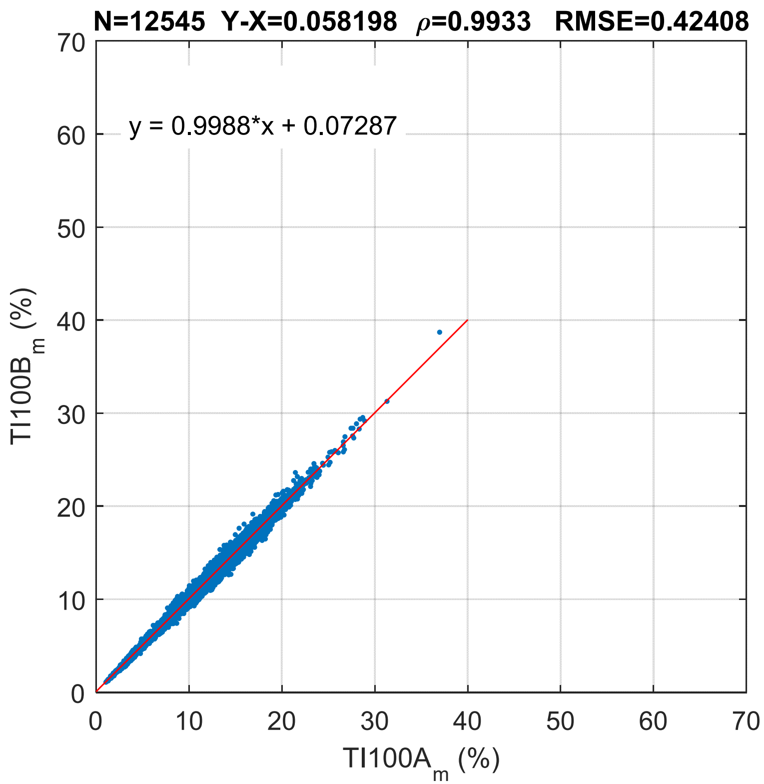
- Data availability is VERY IMPORTANT. Instrument must be very reliable in ALL circumstances.

- Data loss due to environmental conditions or system failures will introduce bias.



TI Typical Results

- TI of two identical anemometers.
- Over one year of data **T>2C. U>8 m/s**
- Y-X = 0.06 is average difference in TI.
- Despite closeness there is small difference of TI (~0.05%)
- If mean TI is 15% the corresponding difference would be 0.06%÷15% = 0.4% of average. Therefore instruments agree very well.
- Average difference is meaningful because it gives an immediate indication of accuracy and whether it is insensitive to outliers and/or timing/synchronization errors.

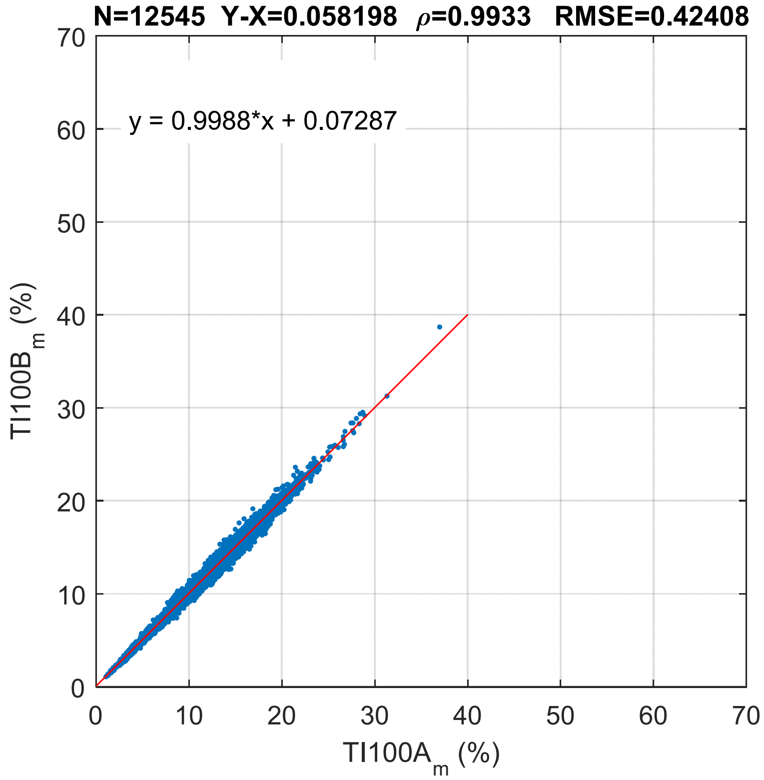


TI Correlation & Regression

- Correlation coefficient (ρ, R^2), measures the amount of linear covariation, is 0,9933 or almost 1. (±1=perfect; 0=no linear covariation.) R^2 is less meaningful because it is mostly subjectively interpreted.
- Regression coefficients slope =0,9988 and offset =0,07287.
- Put simply: Ordinary regression works when y-values have errors or disturbances and x-values are without any. Here both datasets contain errors/disturbances giving us incorrect regression coefficients.

- It would be incorrect to assume that one instrument is incorrect.

T>2C. U>8 m/s.



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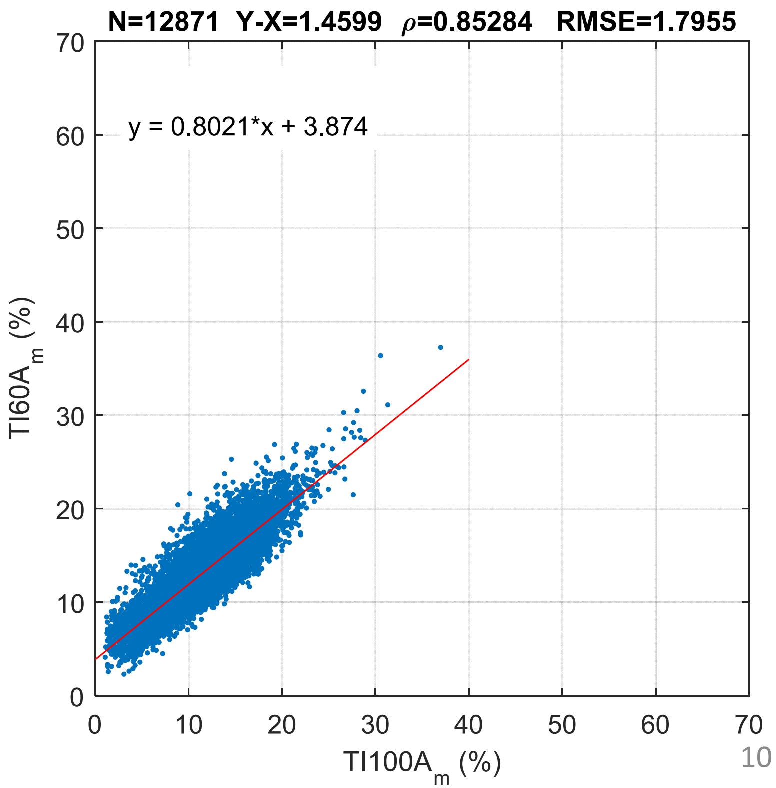
Example 2 – 2 Anems at different heights

- Comparing two anemometers with a height difference of 40m (100m & 60m)
- X-Y = the mean difference, is now 1,5%. This difference is to be expected as wind speed typically increases with height.
- R^2 is now ~0,85.
- It is evident that the R^2 decreases with distance between the instruments. We can realize this intuitively, for example by looking at a river and how the flow at two points is less and less correlated the further the points are from one another because of the eddies and swirls in the water. This is also expressed for example in Davenports formula and specified in the IEC-norm.
- TI also increases at lower heights due to ground “roughness”.

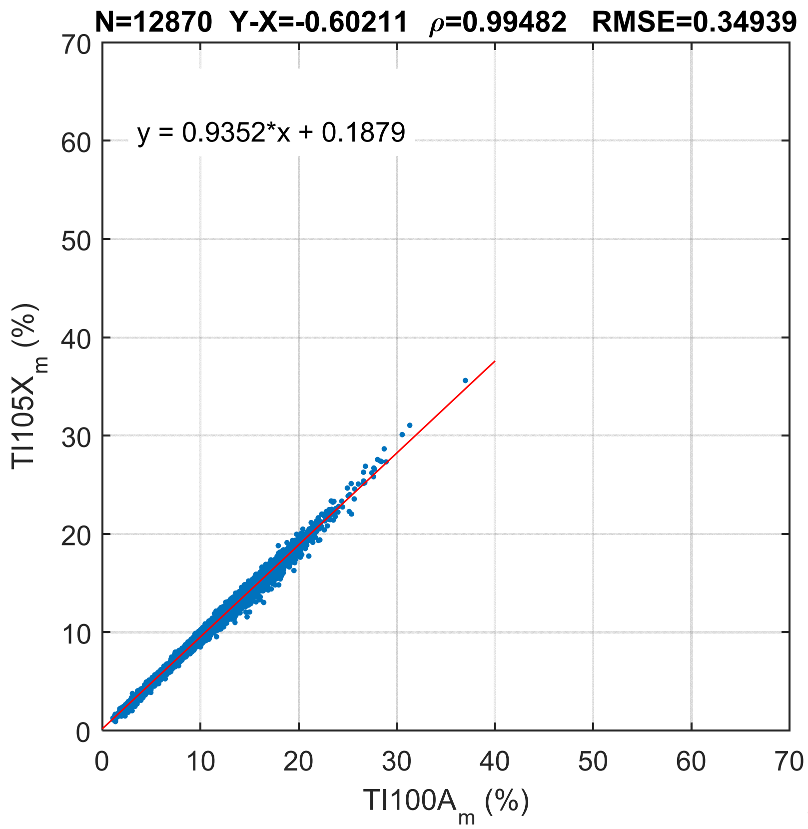
T>2C. U>8 m/s.



EXAMPLE 3 – 2 different anems at same height

- Two different anemometers, cup and ultrasonic at 100m and 105m
- X-Y = the mean difference, is 0.6%. This is a lot considering two similar anems at much larger distance differed by only 1.5% (0.1%/m & 0.04%/m respectively). Turbulence evidently dependent upon instrument type.
- R^2 does not “detect“ this big difference. On the contrary, with a value of 0,999 it says that everything is ok.
- This is because R^2 measures DISTANCE and not QUALITY. The regression coefficients are, as said previously, biased because the assumption of “exact x“ is not fulfilled.

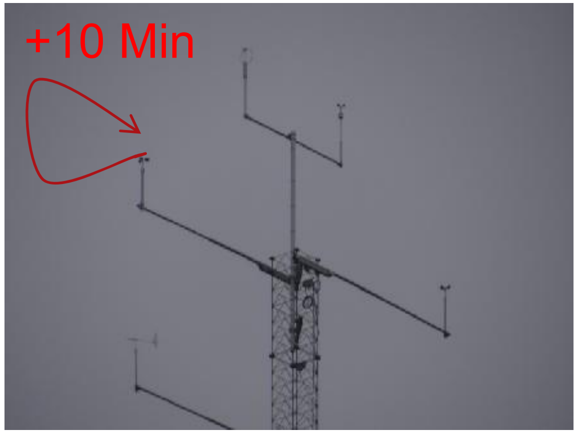
T>2C. U>8 m/s

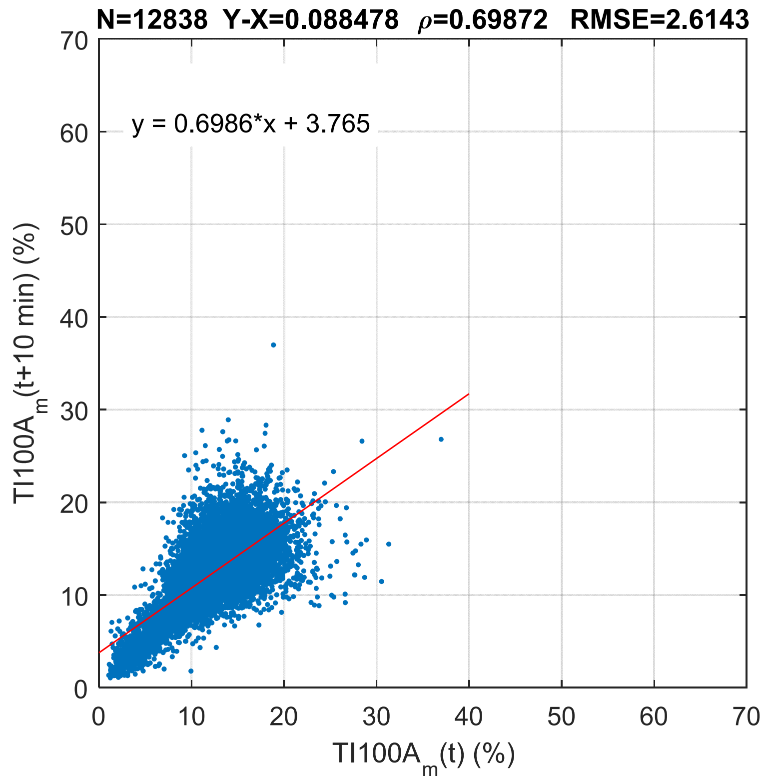


Example 4 – 1 anem only

- One instrument only. x-axis=data from the same anemometer as in all the previous images.
  y-axis = same values displaced by 10 minutes.
- We can really see how meaningful or not the different measures are: Average difference is almost zero as expected. This indicates an excellent correspondence/quality.
- The regression coefficients look very bad. They are different from 1 and 0 (y=x+0) therefore are less sensible measures of quality.
- In this case we could say that they are meaningless because they give the false impression of a very low correspondence between x and y

T>2C. U>8 m/s





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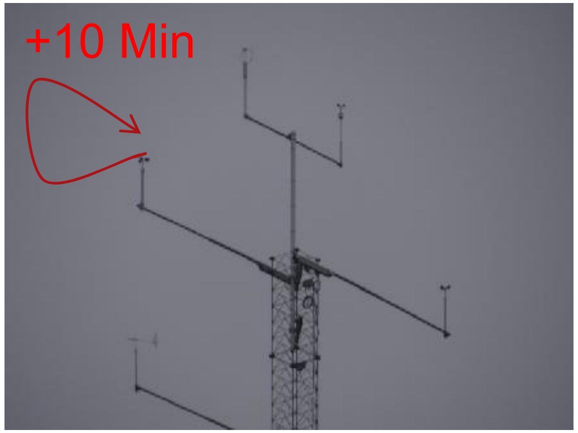
Example 4 continued

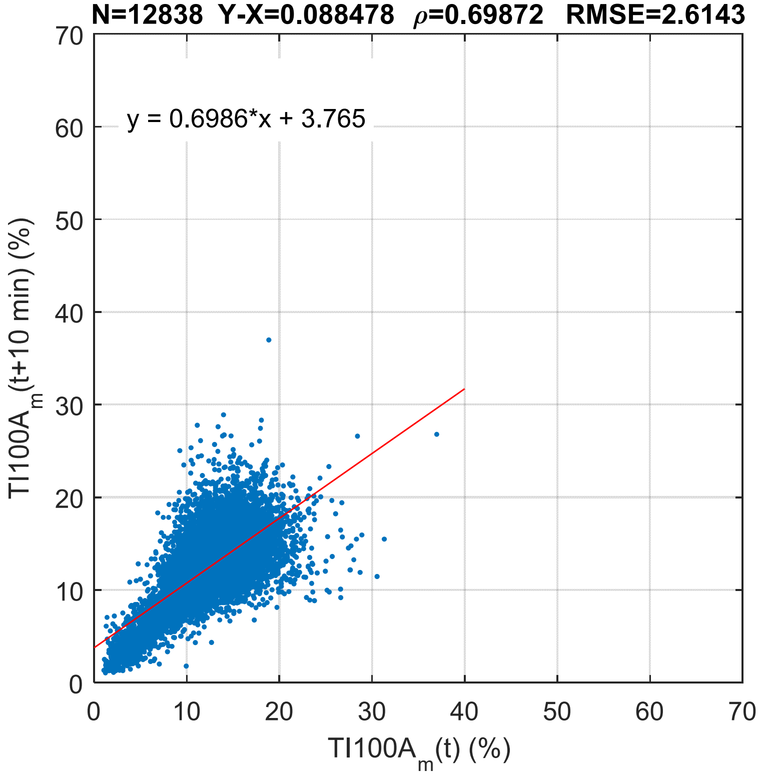
- R^2 is 0,7. So, the R^2 is not meaningful as a quality measure in this context.

- What we see here is the effect of measuring different air volumes – everything else is the same as before. At a wind speed of 5 m/s the size of the volume is 3 km (10 minutes times 5 m/s).

- Evidently the successive air volume are filled with quite different turbulence!

T>2C. U>8 m/s





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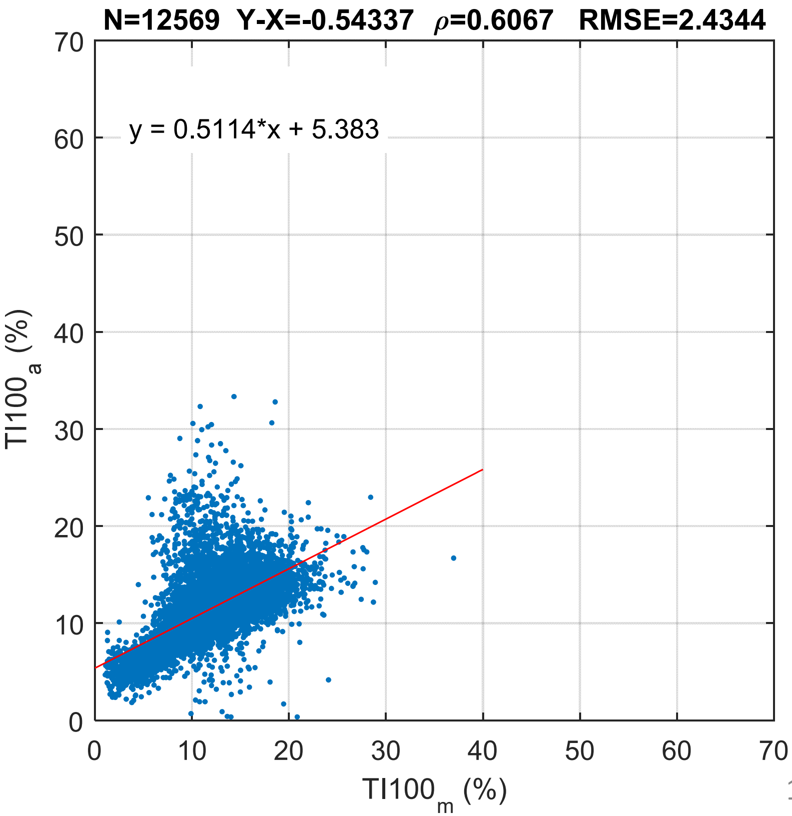
Example 5 – AQ510 and anem 100m

- AQ510 data (100m) compared with cup anemometer. AQ510 was 200m from met mast.
- Data availability (TI) = 98%
- Data availability (WS) = 98%

- The average (absolute) difference X-Y between AQ510 cup anemometer is **-0,5%**.

- As a comparison: the difference between cup and ultrasonic anemometers at the mast top and only 5m apart was slightly larger at 0,6%.

T>2C. U>8 m/s



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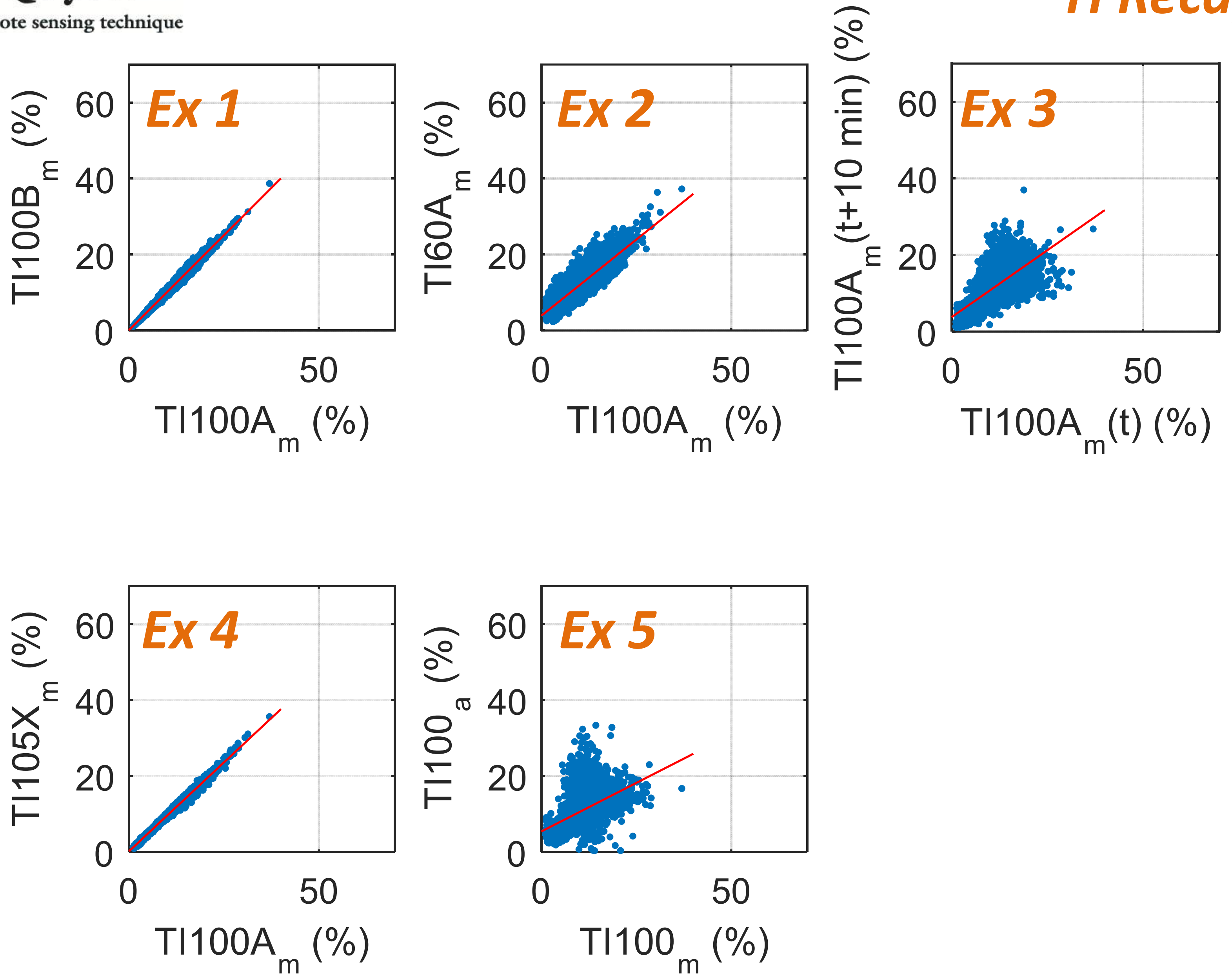
TI Recap



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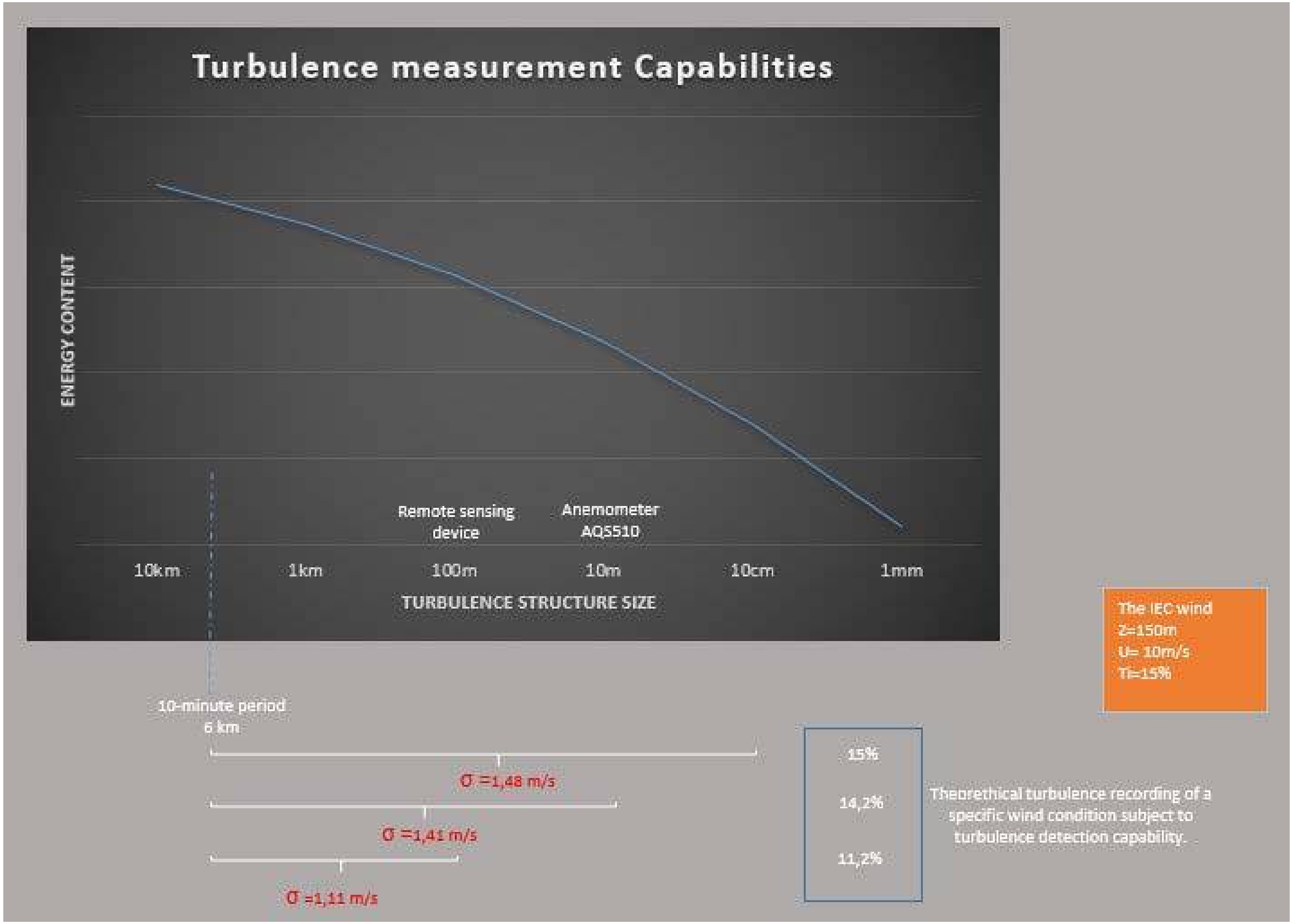
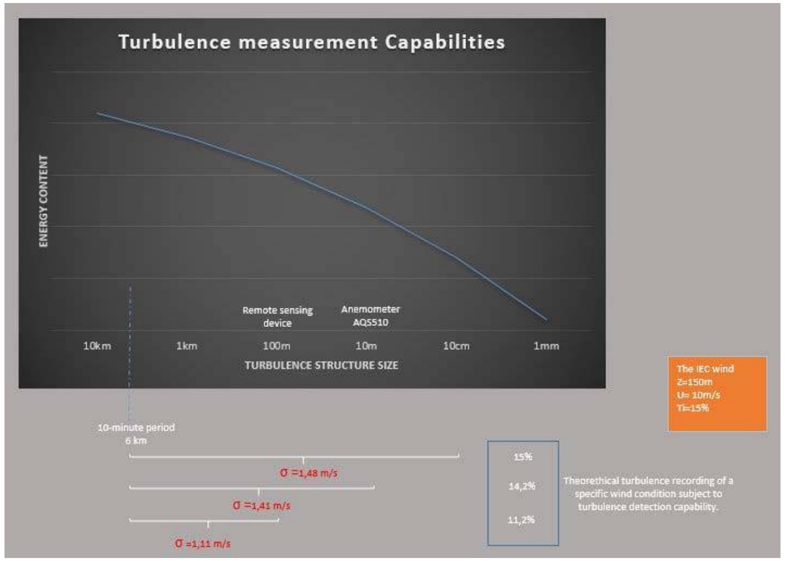
TI Additional comments……



Continued……

- Here we see the turbulence spectrum (blue line). x-axis is size of turbulent structures or “eddies“. With a fixed instrument we can’t see the sizes. Instead we observe the frequency with which they pass by the instrument. Hence, x-axis can also be interpreted in units of frequency. (I have assumed a wind speed U=10 m/s in this example.) y-axis we can see the energy of the eddies of different size. The large eddies contain most energy. Energy is introduced at the largest scales, the turbulence “slices and grinds“ the structures into smaller and smaller ones all the way to under 1 millimetre where the energy dissipates as heat.

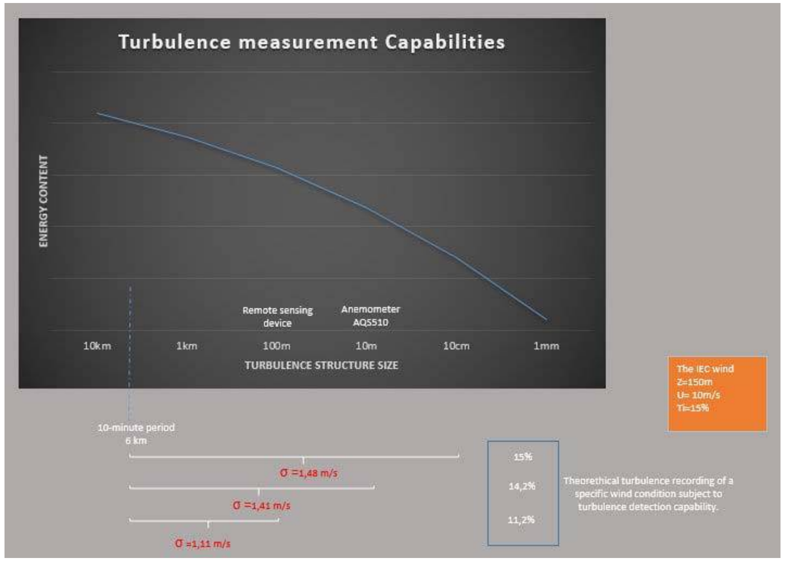


Continued……

- Formally, Energy Content on the y-axis is called Variance Density. The smaller the turbulent structures the less they contribute to the variance
- – i.e. to the turbulence!

- For historical reasons, a 10 minute average is used. The largest scales that we can observe are thus about 6 km at 10 m/s wind (600s x10m/s).

- Another remote sensor (not AQ510) uses a measurement volume of size ~100 m. Thus it cannot see anything smaller than 100m. Variance at scales below 100m is not measured.



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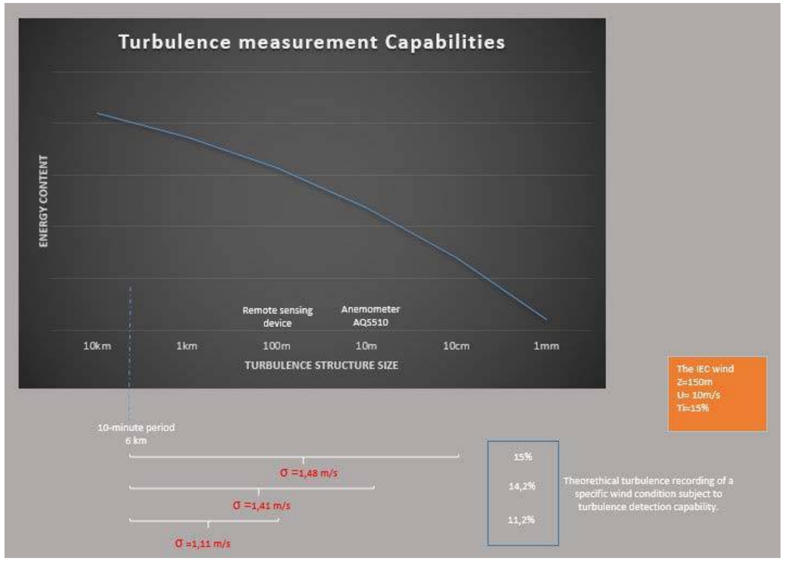
Continued……

- AQ510 measures turbulence at scales down to about 10m. The three sound beams individually measure the turbulence. The large air volume between the sound beams is not used for this. **Thus, AQ510 has the same spatial resolution as a cup anemometer!**



- A cup anemometer needs 5-10 m of air to start due to inertia. It needs even more to stop. The smallest resolved spatial scale for a cup anemometer is thus ~10 m.

- An ultrasonic anemometer has no inertia. Its size is ~10 cm. Smaller scales are not resolved.

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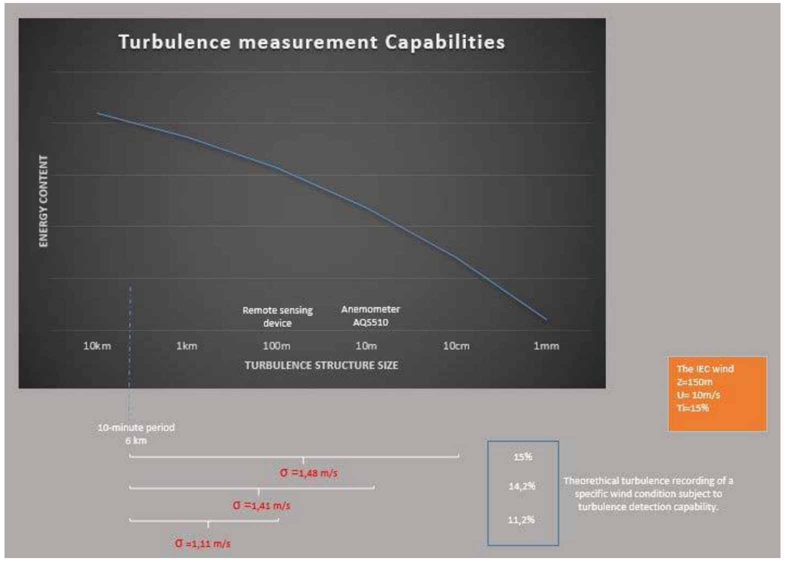
Continued……

- The cup anemometer misses scales below 10m and hence measures a little lower turbulence: 14,2%.

- A remote sensor with a measurement volume of ~100 m would only measure 11,2 %. **Again AQ510 is not affected by this!**

- An ultrasonic anemometer has no inertia. Its size is ~10 cm. Smaller scales are not resolved.



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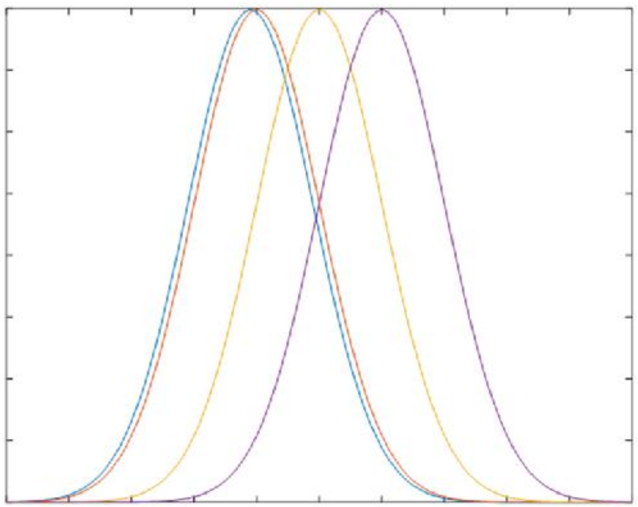
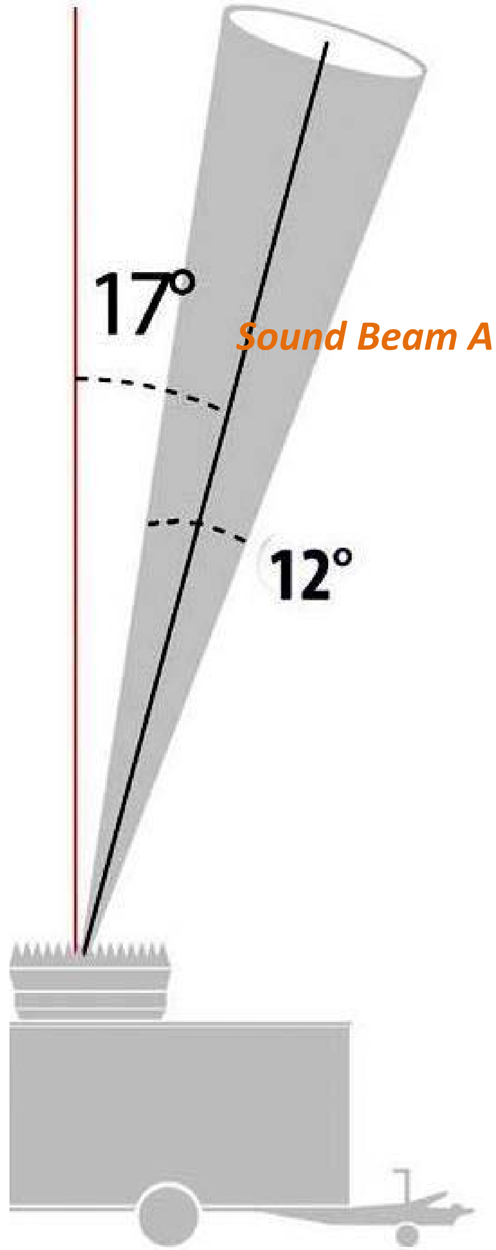
HOW DOES AQ510 WORK?

- An acoustic pulse is emitted 144 times in every 10 minutes. As the sound pulses pass through the air a certain amount is continuously reflected by small temperature variations.

- The return signals are analyzed and a bell shaped spectrum is created. The spectra are then added together.

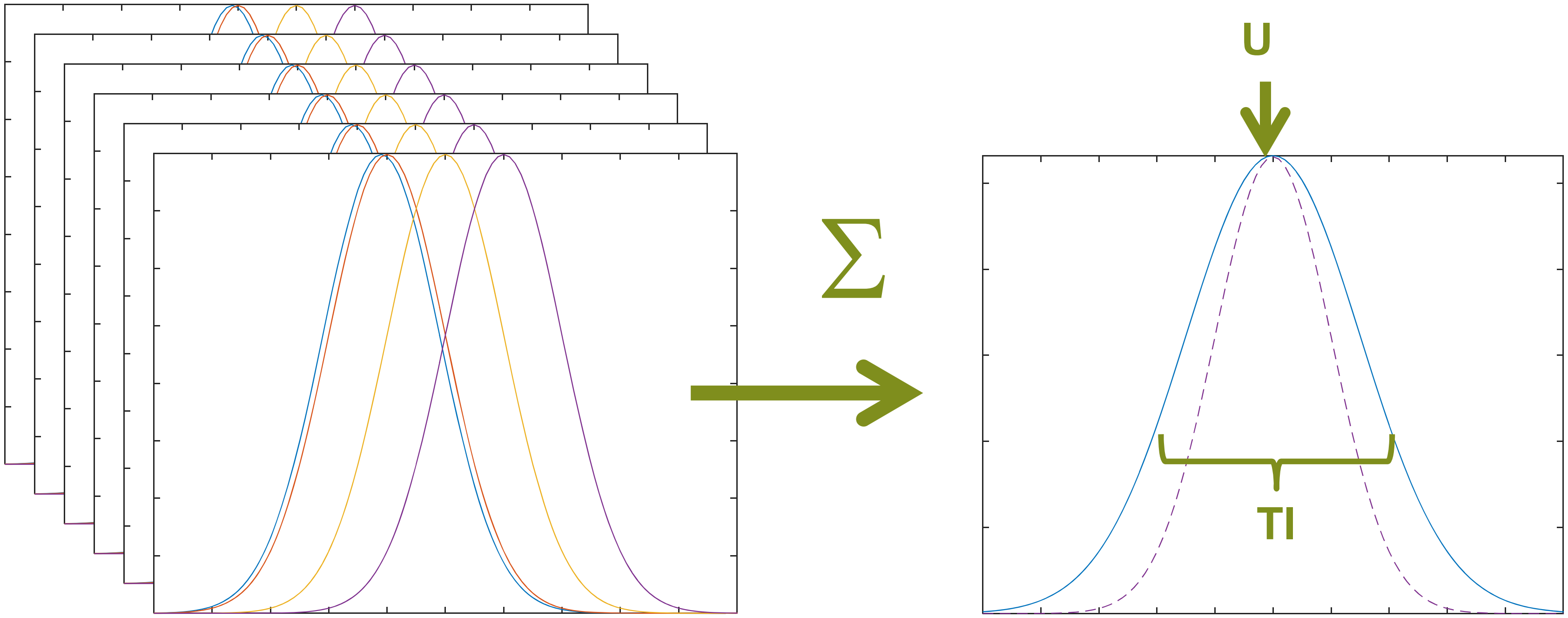




AQ510 in trailer.

TI AQ510

- By summing single spectra for each beam a stable mean spectrum is obtained.
- The peak position U is proportional to the mean wind speed. The width TI gives the turbulence. The values represent the values of U and TI in a 5 m height interval.



- AQ510 does not use whole 100m air volume. Only the ~10m individual sound beam volumes are used.

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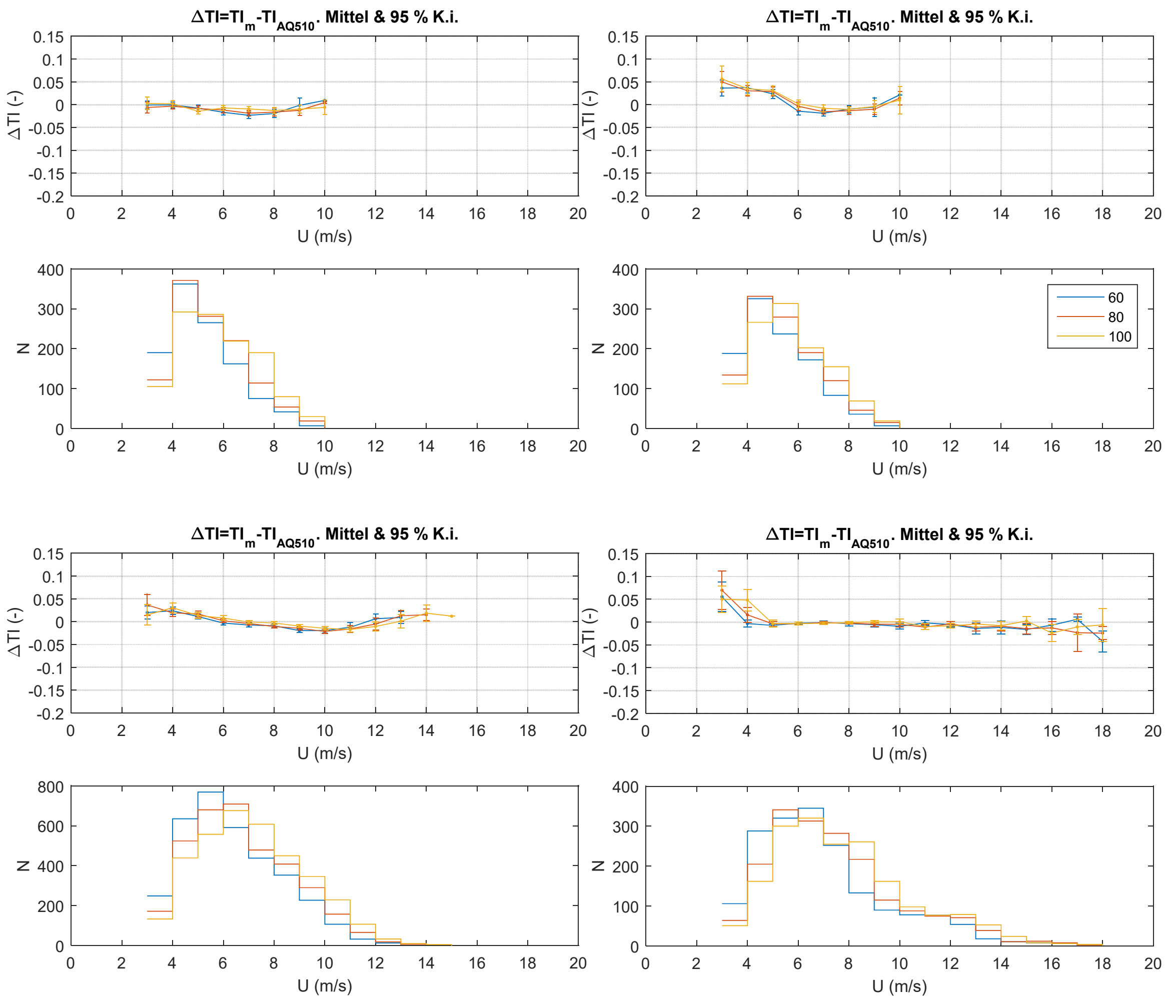
4 x AQ510

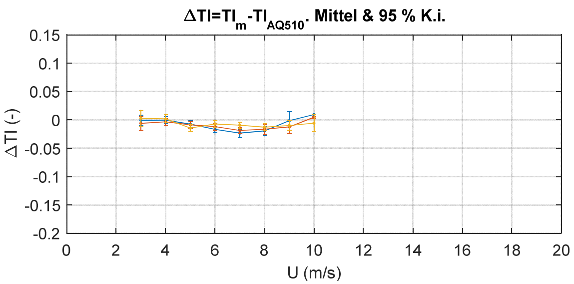
Four AQ510 Systems. 12-15 Measuring days

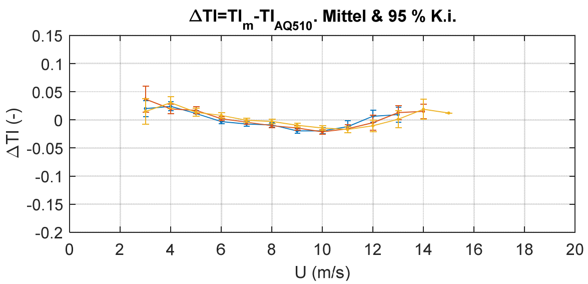
Every picture shows the difference in TI between AQ510 and the cup anemometer versus wind speed at three heights: 60, 80 and 100 m. (No lee or iced observations). The mean difference with 95 % confidence intervals are shown for 1 m/s wind speed classes.
Also, the corresponding histograms (number of observations per bin).

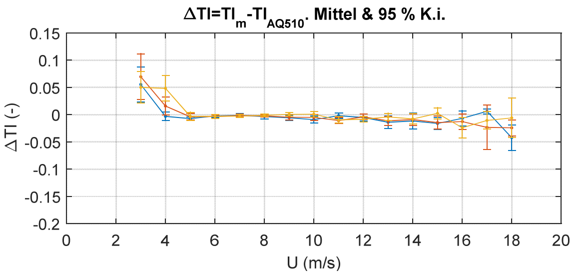


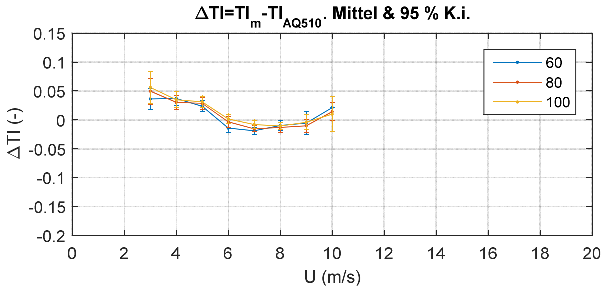
Four AQ510 Systems. 12-15 Measuring days

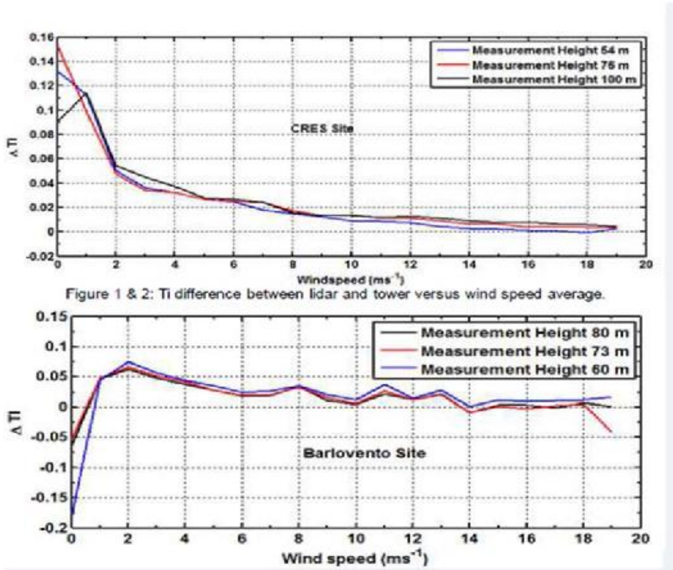
Here compared with results from a LiDAR.
(The scales are chosen to be exactly the same as for the LiDAR).





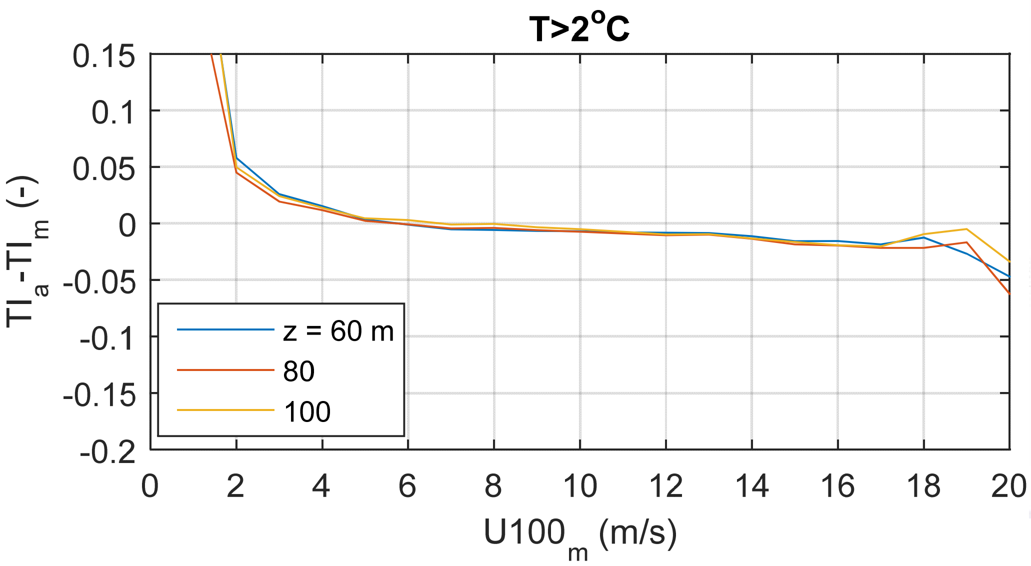






AQ510 and LiDAR

- And here finally for a longer term measurement (358 days) with AQ510 in the same style.



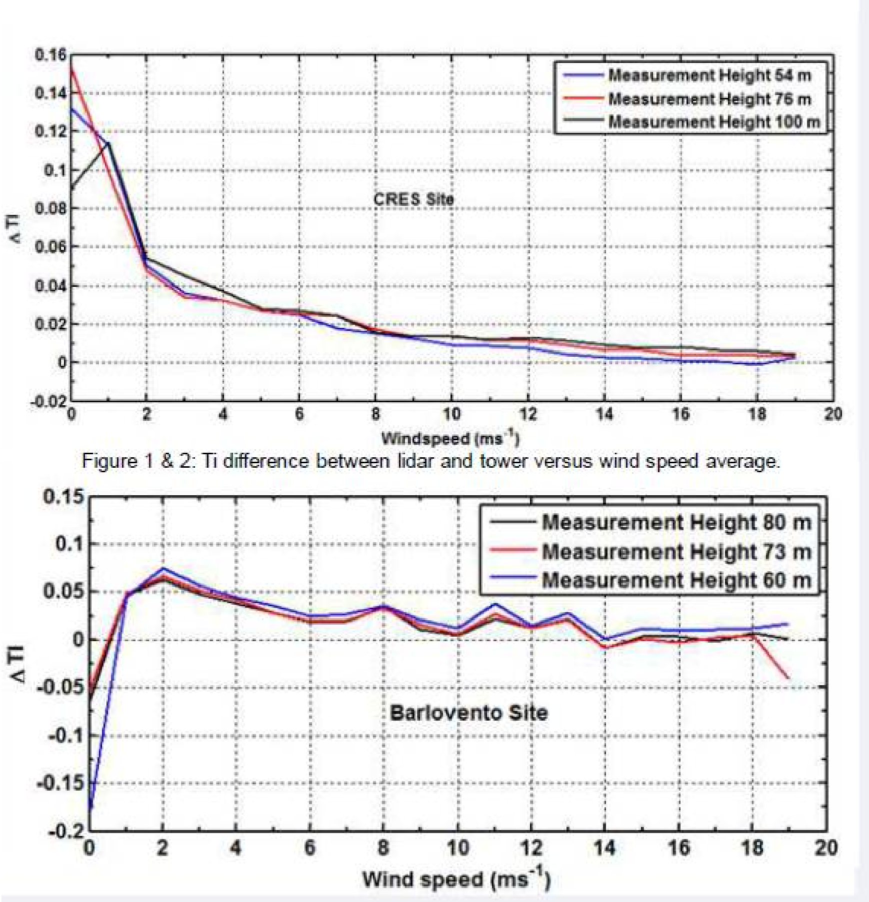


Figure 1 & 2: Ti difference between lidar and tower versus wind speed average.

TURBULENCE INTENSITY MEASUREMENTS FROM A VARIETY OF DOPPLER LIDAR INSTRUMENTS,
R Krishnamurthy, M Boquet, M Machta. LEOSPHERE SAS, FRANCE. EWEA 2014 Poster 080.

CONCLUSIONS

- Turbulence is more complicated to measure than WS.
  Instrument properties such as volume, resolution, inertia and directionality of turbulence are very important.

- The average difference between two instruments is a meaningful and robust measure of agreement.

- Regression coefficients and correlation coefficient (R^2) are not suitable, not robust, or even sensitive and biased when applied to TI.

- Based upon sample data sets from five (5) AQ510 systems:

  4 x 2 weeks
  1 x 52 weeks

  Data availability for WS good at 98%
  Data availability for TI good at 98%

AQ510 underestimates TI by ~1%

Author – Lasse Johansson,
Senior Wind Consultant at SWECO

Edited and with additional information by Colin France, Business Development Manager, AQSystem

Lasse Johansson is Senior Wind Consultant at SWECO, Sweden.
He studied maths, physics and oceanography at Gothenburg and Kiel Universities and holds PHD's in meteorology and oceanography from Stockholm University. Lasse was a consultant oceanographer with the Swedish Meteorological and Hydrographic Institute for over eight years and has worked within the wind industry for ten years.

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