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Variations in the power-law index with stability and height for wind profiles in the urban boundary layer

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Contents

Background & Study objective

Background: the Power law

Power Law (PL)

- The PL is one of the most common empirical profiles to express the vertical distribution of horizontal wind velocities in boundary layers.
- The power-law index (PLI, α) is determined according to the terrain roughness.
  - Davenport (1960), Counihan (1975), Tamura et al.(1999) etc.

$$V_Z = V_G \left(\frac{Z}{Z_G} \right)^{\alpha}$$

V_Z = mean velocity at height Z,
V_G = gradient velocity,
Z_G = gradient height,
α = power-law index

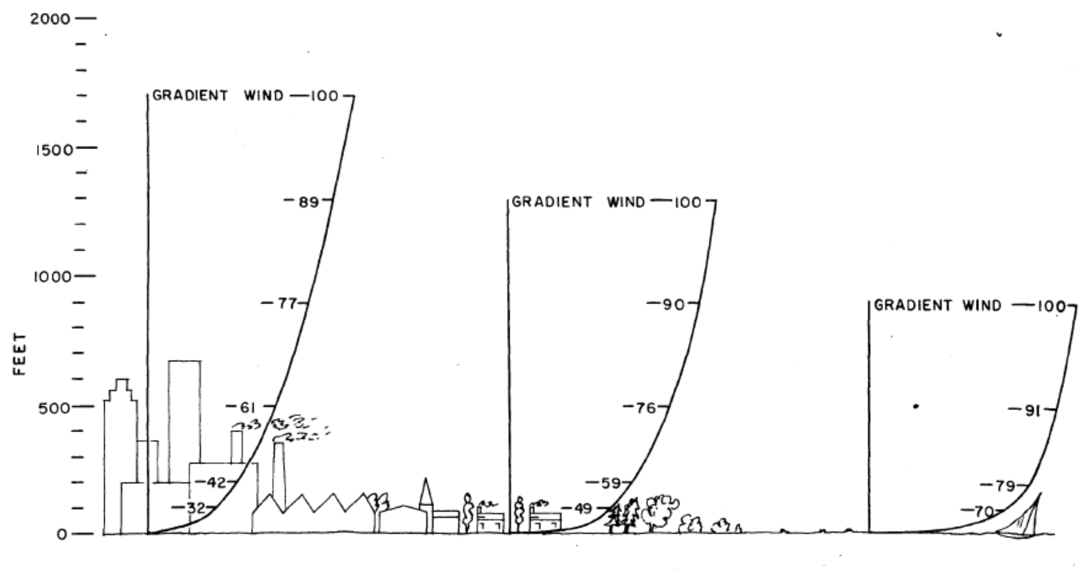
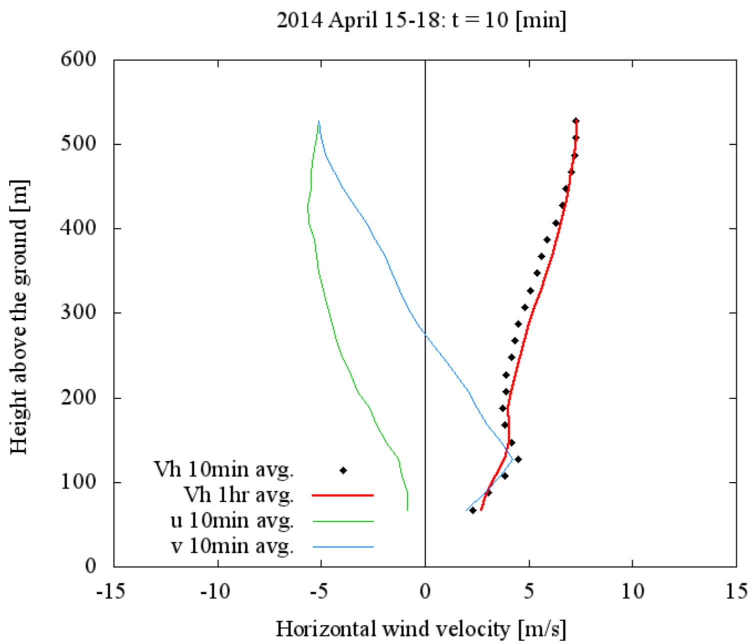


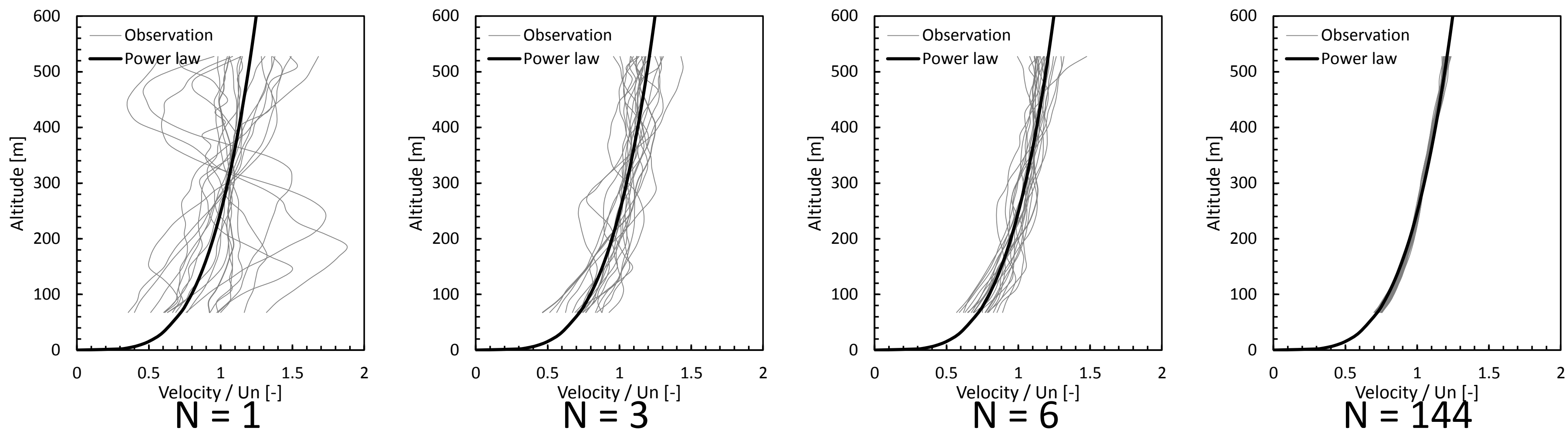
FIG. 2.3 PROFILES OF MEAN WIND VELOCITY OVER LEVEL TERRAINS OF DIFFERING ROUGHNESS

Davenport (1961)

Background: Wind profiles to be modeled



- Instantaneous wind profiles are difficult to be fitted to the PL with sufficient accuracies.
- A large number of actual profiles needs to be averaged to draw the PL-like profile.



Ensemble averaged wind profiles（Ensembles of 10 min average velocity)

Background: How is the PL valid?

- The PL was originally proposed for wind profiles of **extremely strong wind situations** in structural engineering. (Davenport, 1960)
  - High velocity and neutrality of atmosphere are prerequisites of the PL.
- The PL has been applied in analysis of wind environment and air pollution
  - because of the simple mathematical expression
  - because of wide valid area along the height (Counihan, 1975)
    - » Wind tunnel: Takahashi & Murakami(1982), Li & Meroney (1996), Uehara (1996) …
    - » CFD: Murakami & Mochida (1988), Baik & Kim (1999), Tominaga et al. (2008) …
- The PLI depends on the stability and height at which the PL is evaluated. (Irwin, 1979; Hanafusa, 1986)
- The accuracy of the PL is not assured for a wind profile
  - with **a low wind speed**
  - under **non-neutral condition**
  - which covers **high ground heights**

Study objective & Method

Study objective

- Measurement of vertical wind profiles in the atmospheric boundary layer which develops above urban area with
  - a high spatial resolution (Δz = 20 m)
  - a temporally continuous observation (10-min avg. profiles in 7 months)
- Investigation of
  - validity of the Power Law (PL)
  - variability of the Power-Law Index (PLI, α) according to
    - wind velocity, atmospheric stability, and height

Method

- Wind profile measurement using a Doppler Lidar System (DLS)
- Turbulent flux measurement of the heat and momentum with Eddy Covariance Method (ECM) using an Ultrasonic Anemometer (UA)
- In densely developed urban area (Tokyo JAPAN)

Observation site & Instrumentation

Observation conditions

☐ Site: Tokyo JAPAN

- The center part of Tokyo
- DLS on a building rooftop at the I.I.S., the Univ. of Tokyo
  - latitude: 35°40'N; longitude: 139°41'E
  - altitude: 40 m; ground height: 27.5 m
- UA (ECM) on a tower at the Tokai University campus
- Surroundings of the site: Residential areas
  - some large greenery areas
  - commercial areas in a few kilometers away

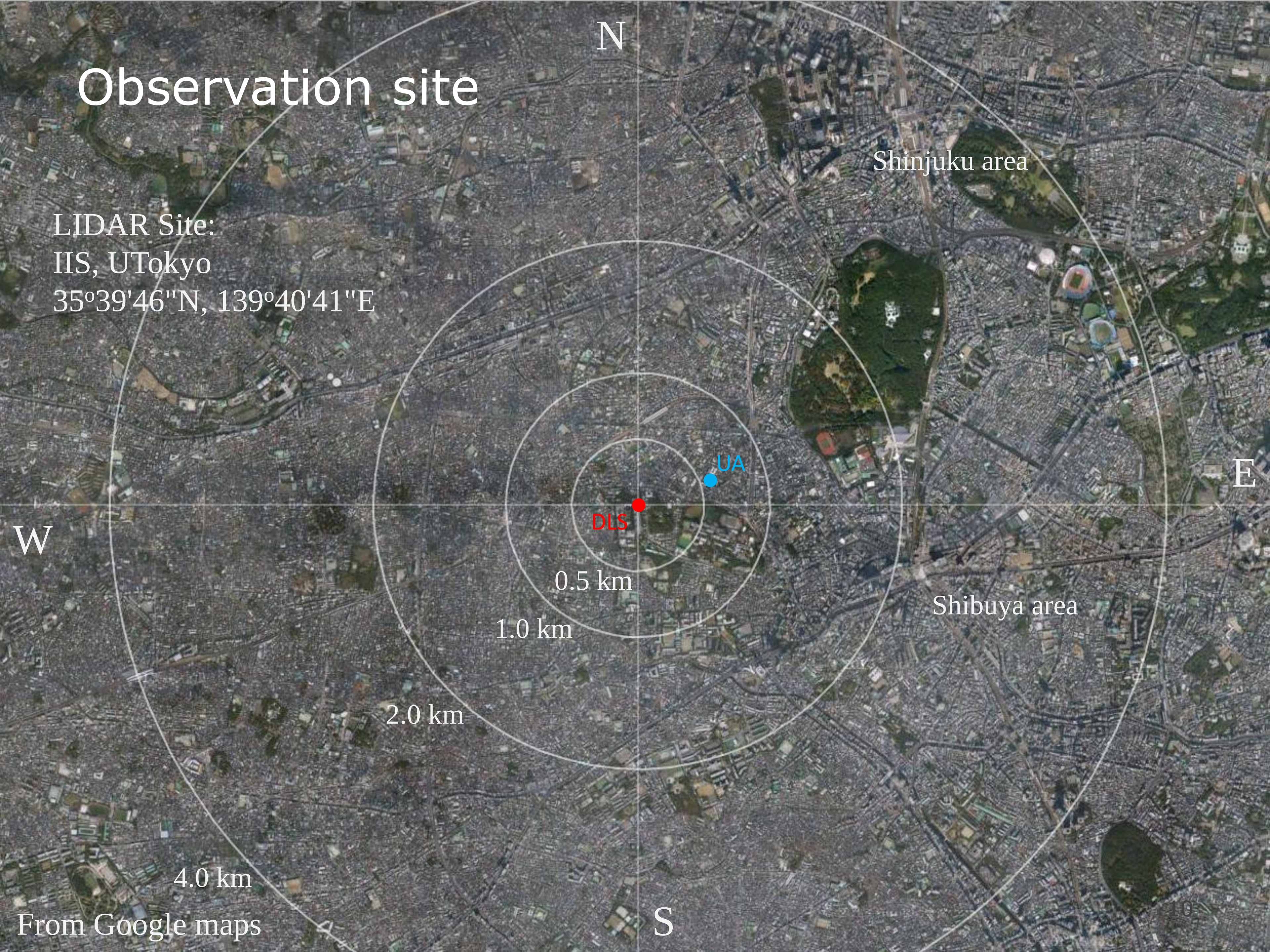
☐ Observation period: 7 months

- Sep.-Dec. in 2013 and Apr.-Jun. in 2014

☐ Measurement height:

- DLS: 67.5 - 527.5 m
  - for every 20 m (24 levels)
- UA (ECM): 52 m

DLS installed in I.I.S


Observation site
N
Shinjuku area
LIDAR Site:
IIS, UTokyo
35º39'46"N, 139º40'41"E
UA
E
W
DLS
0.5 km
1.0 km
Shibuya area
2.0 km
4.0 km
From Google maps
S

Observation site: DLS and UA

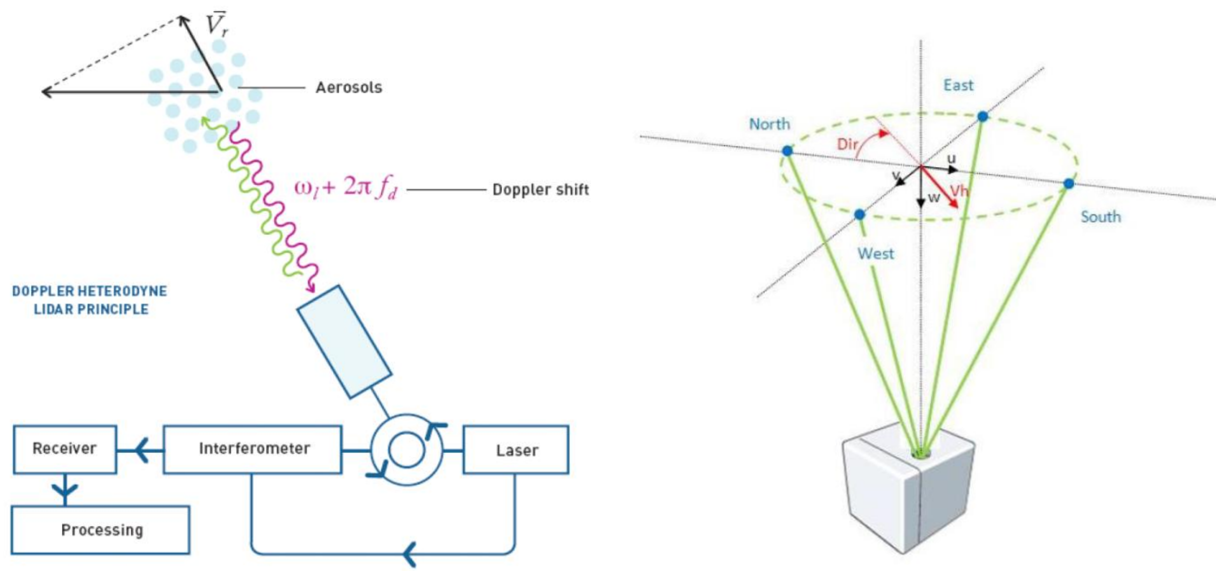
Shinjuku area

Shibuya area

Doppler lidar system: DLS

☐ Principle of measurement

1. Emission of pulse lasers (λ = 1.54 μm)
2. Scattering of the laser by aerosols
3. Measurement of velocity component in the line of sight using the Doppler shifts of the scattered light
4. Calculation of 3D velocity components from vector synthesis of 4 directions

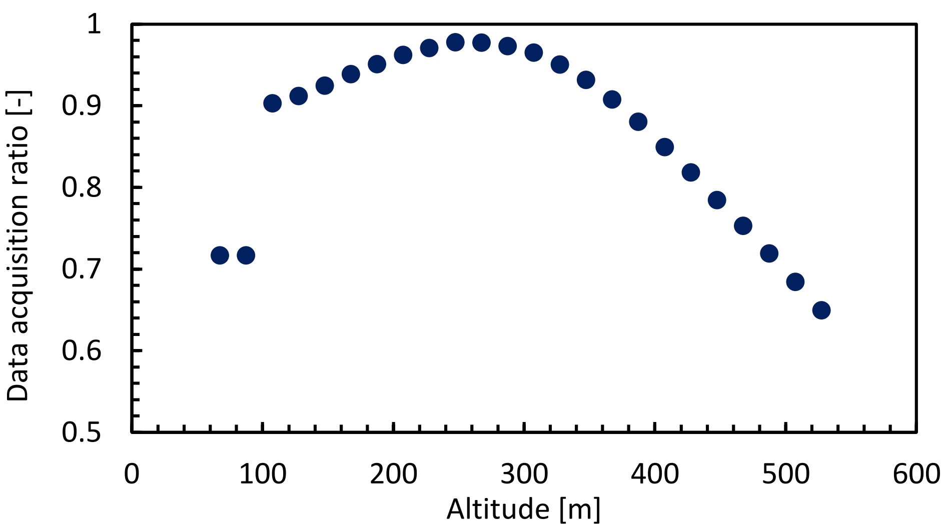


Measurement principle of a heterodyne Doppler Lidar

(Thobois et al. (2014), ICWE14)

Data in Analysis & Data acquisition ratio

- Only horizontal wind velocity were analyzed. No vertical wind component.
- Data acquisition ratio (DAR) in 10-min avg. profiles
  - Highest at z = 247.5 m (97.7%)
- The wind profiles in which velocities at all height levels could be measured were used for the analysis.
  - DAR of 10-min profiles during the observation period = 58.9%



Height and data acquisition ratio
(10-min avg.)

Number of available data
(10-min avg.)

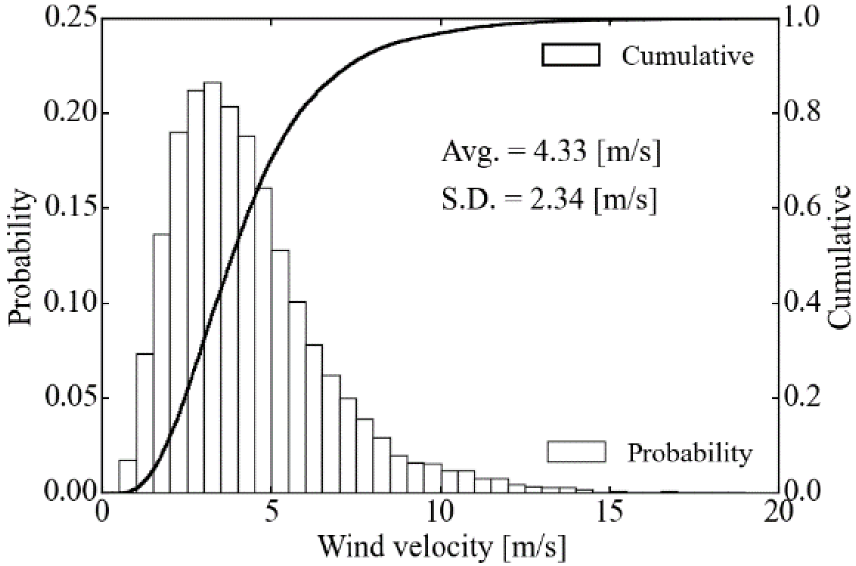
Year / Month	Number of available data	Acquisition ratio [%]
2013 / 9	3441	83.5
2013 / 10	2707	60.6
2013 / 11	2200	50.9
2013 / 12	1080	24.2
2014 / 4	2907	68.1
2014 / 5	3070	68.8
2014 / 6	2523	58.4
Total	**17928**	**58.9**

Observed data

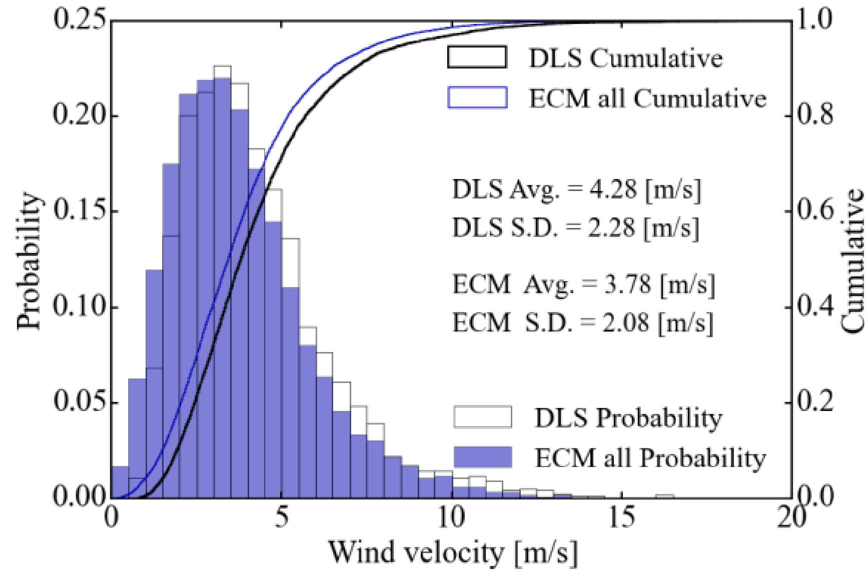
Wind velocity during the observation

☐ Frequency distribution of the horizontal wind velocity

- u_b = wind velocity measured at the lowest level in the DLS (z = 67.5 m).
- Mean u_b (10 min avg.) = 4.3 m/s; u_b <5 m/s for 60% of the time.
- Frequency distribution shape was very similar in the DLS and the ECM.
  - The two measuring sites were assumed to reflect the same wind environment.



(i) 10 min average

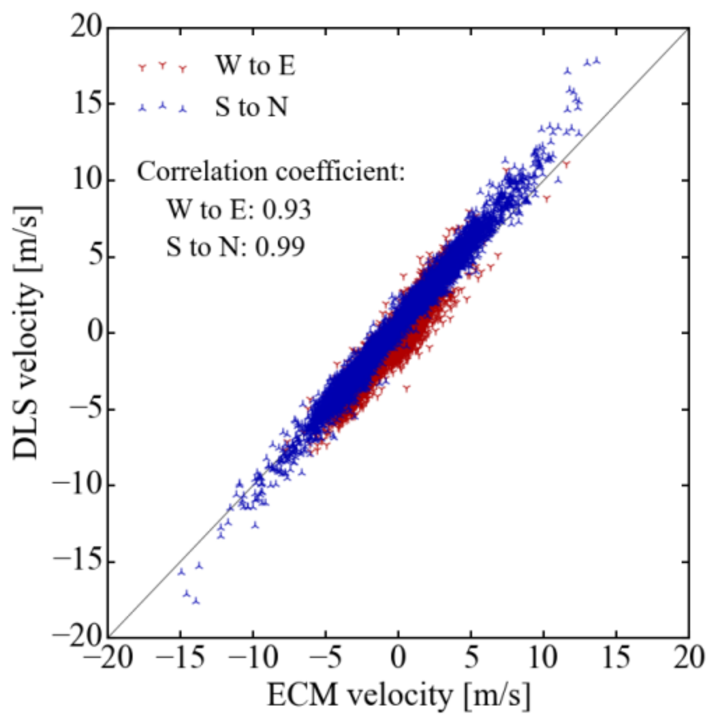


(i) 30 min average

Probability and cumulative density functions of the horizontal wind velocity measured by the DLS (u_b, z = 67.5 m) and ECM

Wind velocities in DLS and ECM

- Velocities of the west and south wind components
  - Correlation between the DLS and ECM was very high.
    - The DLS and ECM data could be assumed to be measured at the same location.

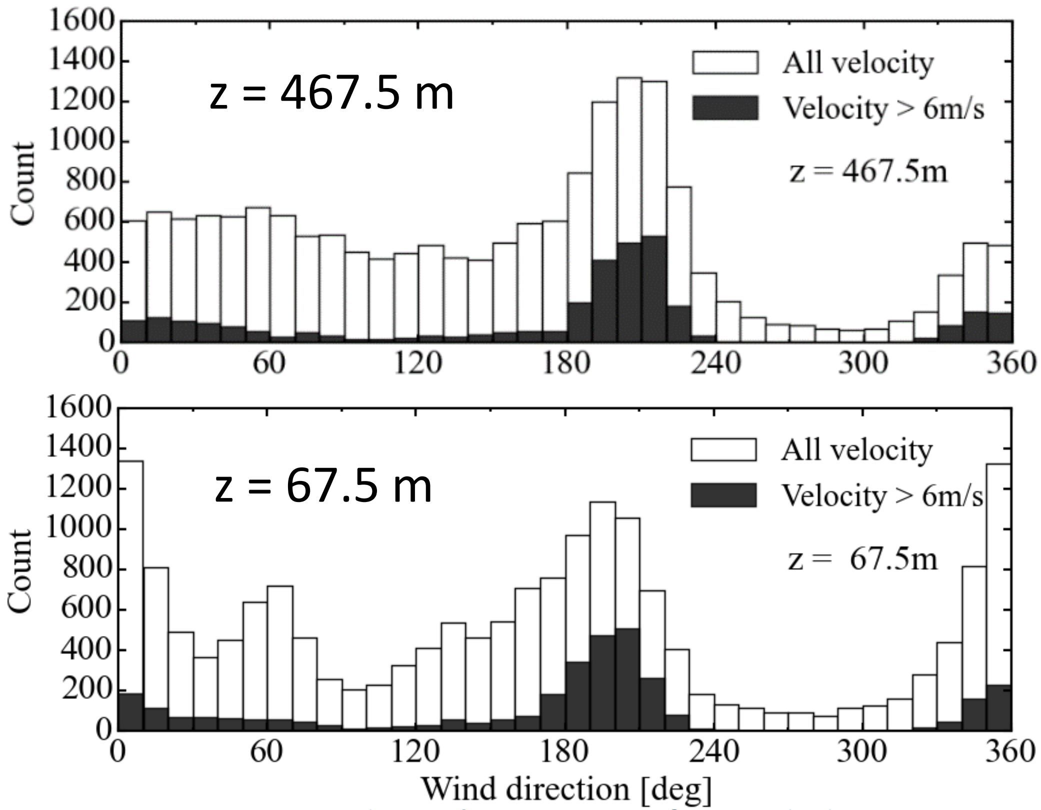


Correlation of the wind velocities from the ECM (52 m) and DLS (67.5 m)

The west and south wind components for the 30 min average are compared.

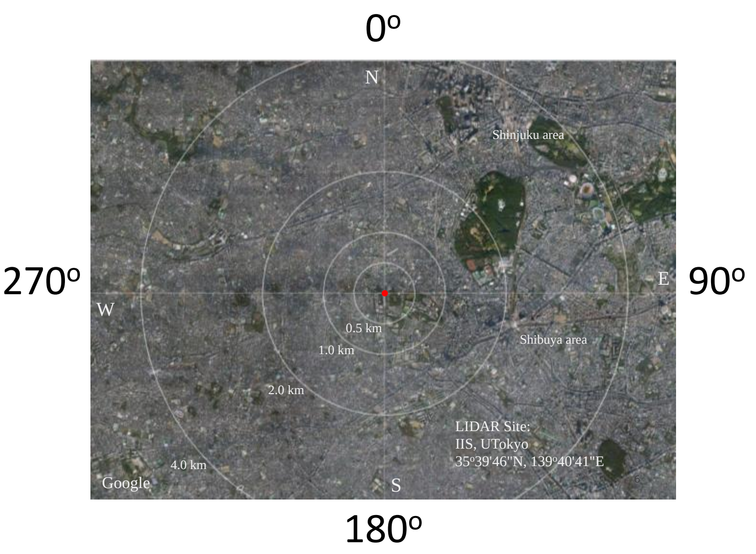
Wind directions during the observation

- Many of wind profiles were measured as south and north wind.
- Differences in the frequency distribution between heights are small for higher velocities.



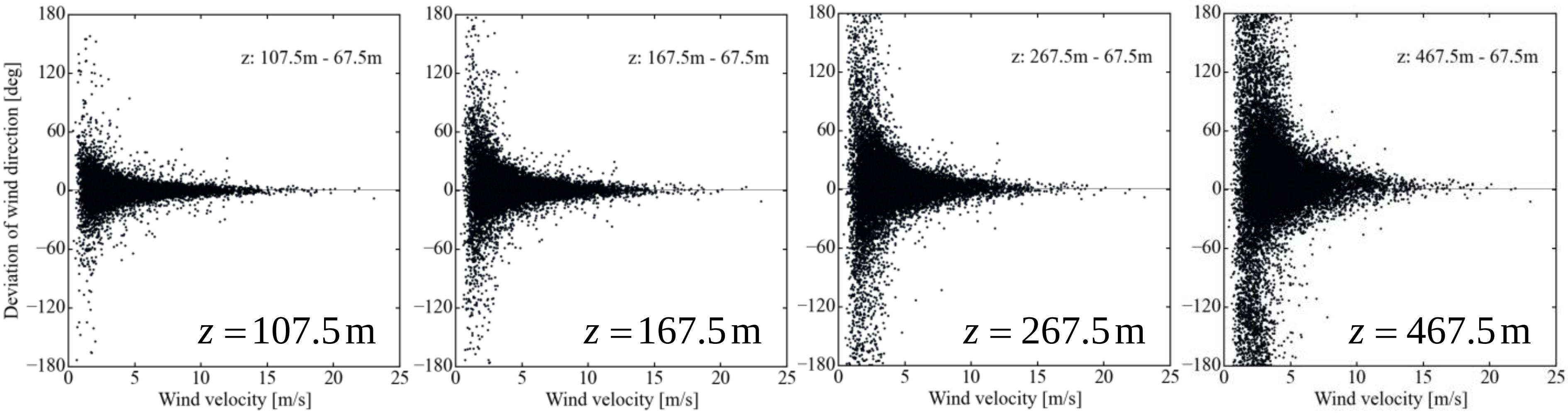
Frequency distributions of wind directions

10-min avg.; High velocity is extracted from velocity@67.5 m.



Wind velocity and wind-direction deviation

- The deviation tended to increase with the increase in height difference.
- The deviation decreased with the increase in wind velocity for all heights.
- When u_b <5 m/s, the deviation was very large
  - The determination of the prevailing wind direction was very difficult.

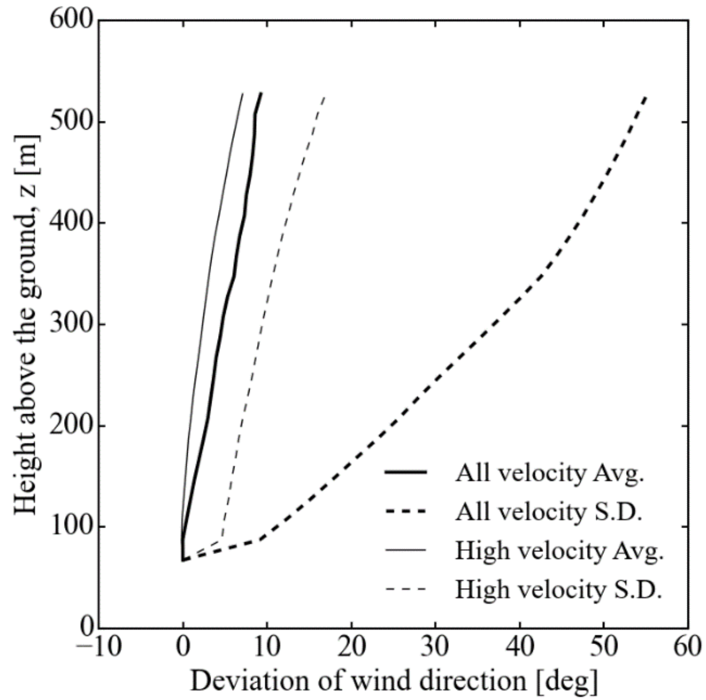


Relationship between the wind velocity and deviation in the wind direction

Based on the wind velocity (u_b) and direction (wd_b) at a height of 67.5 m; 10 min average

Average deviation of wind direction

- The wind direction deviation became very large for all wind velocities.
- The mean deviation became small for high wind velocity data
  - 7° at the highest observation point.

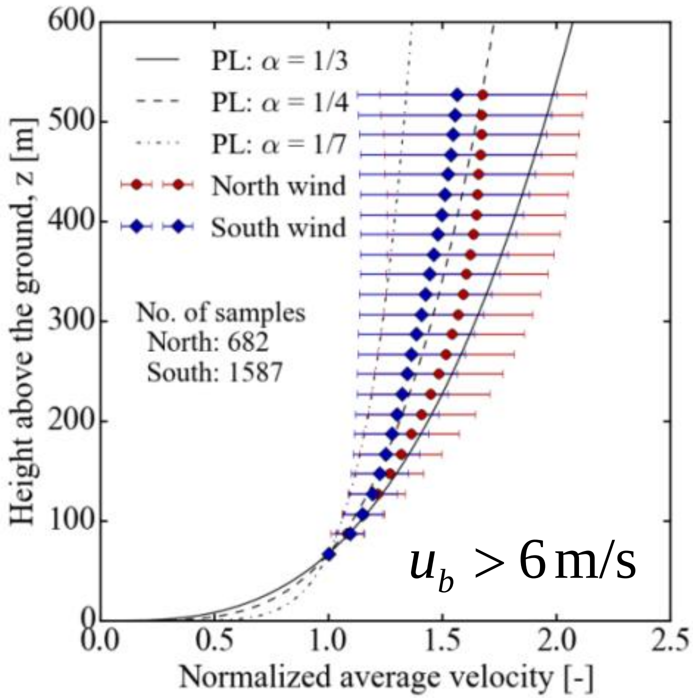


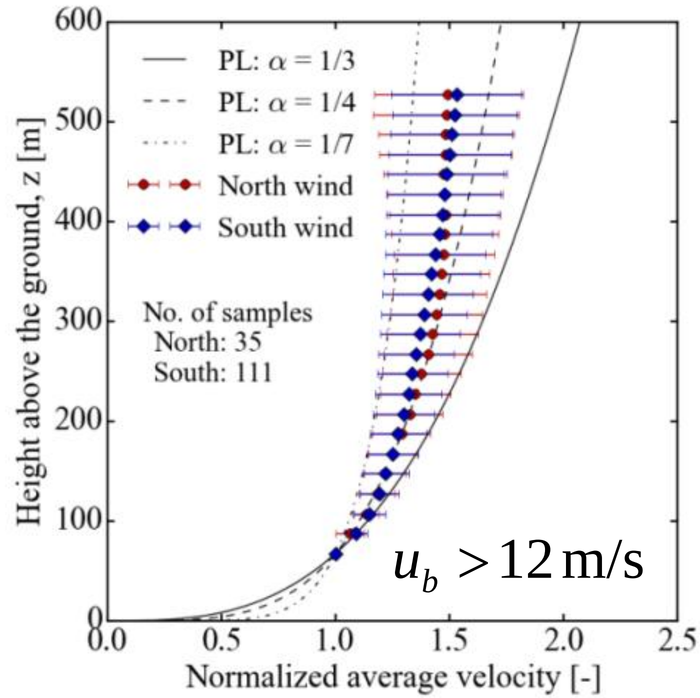
Vertical profiles of the average (Avg.) and standard deviation (S.D.) of the wind direction deviation in relation to the direction at a height of 67.5 m

The high velocity data corresponds to wind velocities $u_b \geq 6$ m/s.

Average wind profile (high velocity)

- The mean velocity could be fitted using the PL below 200 m high.
- When u_b >12 m/s, the PLI difference depending on the wind direction decreased, with a PLI of 1/4 allowing a good prediction of both north and south wind profiles.





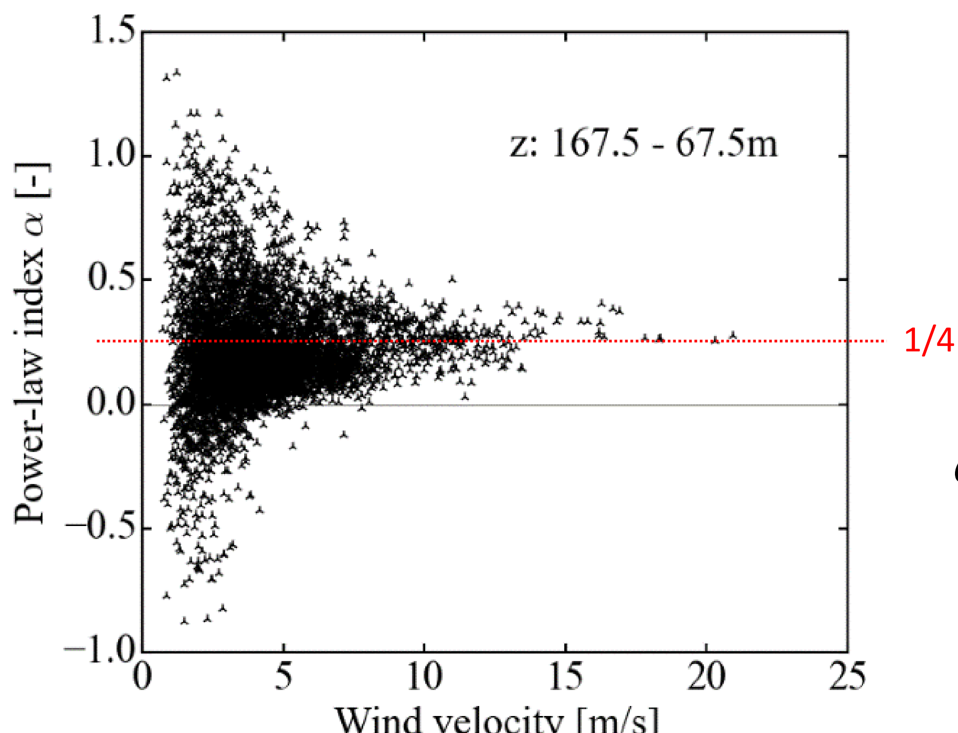
Ensemble-averaged profiles of the wind velocity based on the 10 min average

The error bars show the standard deviation of the profiles.

North wind: $0 \le wd_b < 20°$ or $340 \le wd_b < 360°$, South wind: $180 \le wd_b < 220°$

Wind velocity and PLI

- With the decrease in wind velocity, the PLI exhibited a larger variety.
  - Sometimes PLI reached negative values.
- For high wind velocities, the PLI converged to around ¼ (0.25).



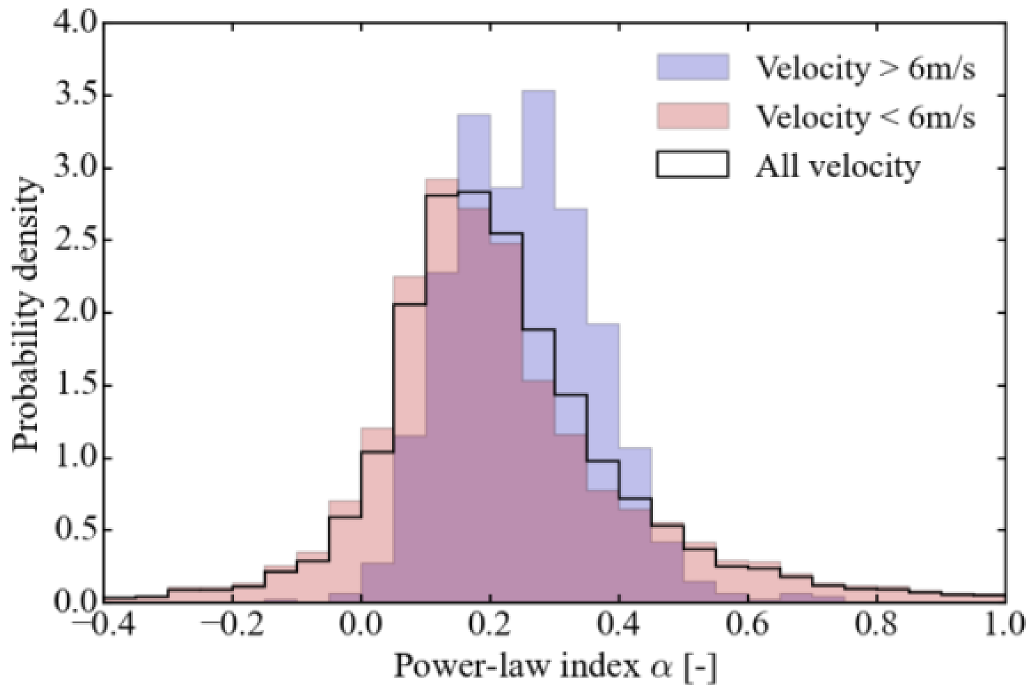
$$\alpha = \frac{\ln(u_2/u_1)}{\ln(z_2/z_1)}$$

Wind velocity (u_b) and PLI (α)

PLIs were derived from the 30 min average of the wind velocity at 67.5 and 167.5 m.

Probability of PLI

- The PLI tended to be smaller for low wind velocities.
- The mode of the PLI for all velocities was about 0.15, with the distribution shape having a long tail towards a larger PLI.

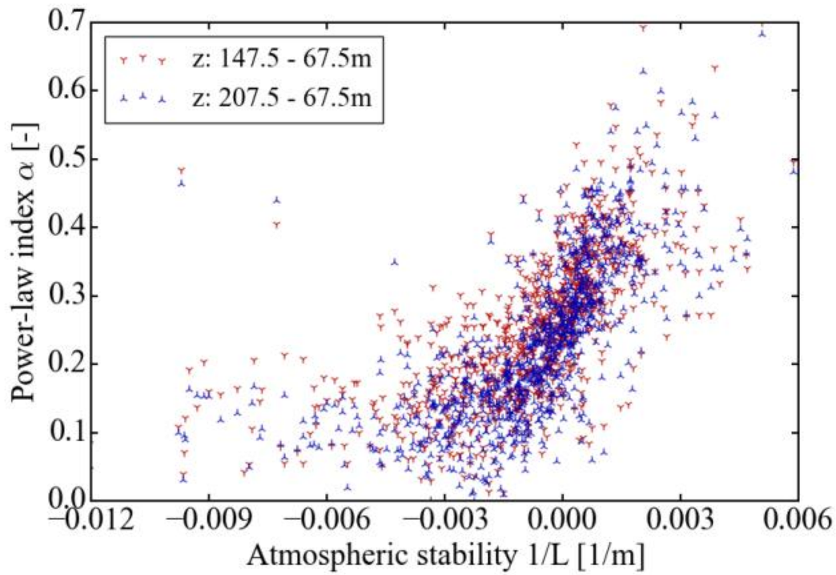


Probability density functions of the PLI

PLIs were derived from the 30 min wind velocity average at 67.5 and 167.5 m high.
The data are divided in high and low velocity using u_b.

Atmospheric stability and PLI

- Neutral (1/L = 0): PLI = 0.2 ~ 0.3
- Unstable (1/L < 0) : PLI became small
  - The PLI remained around 0.1 until a certain level of instability was reached.
- Stable (1/L > 0) : PLI became large
- The height difference when deriving the PLI did not result in large differences .



$$L = \frac{-u_*^3 T}{\kappa g Q}$$

L: Monin-Obukov length
u_*: friction velocity
T: temperature
κ: von Karman's constant
g: gravitational acceleration
Q: temperature flux

Relationship between the atmospheric stability (1/L) and the PLI

The Monin-Obukhov length L was calculated from the ECM.
The PLI was determined from 30 min wind velocity for heights of 67.5 and 147.5 or 207.5 m.
Data for $u_b \geq 6$ m/s were used.

Conclusions

Concluding remarks

- A DLS and an UA (ECM) were simultaneously installed to measure wind profiles and the atmospheric stability in the urban boundary layer of Tokyo, Japan.
- For high wind velocities (u_b > 6 m/s)
  - The PL could be used to model the mean wind profiles for the lower boundary layer (z < 200 m).
  - The PLI converged to **1/4** (0.25).
  - The effect of the atmospheric stability on the power-law index could be connected with the inverse of the Monin-Obukhov length.
- For low wind velocities
  - u_b (10 min avg.) **<5 m/s** during **60%** of the observation period.
  - The differences in wind direction with height were very large.
  - The PLI was smaller (~ **0.15**) on average.
  - The PLIs' large variability resulted in
    - a difficult definition of a representative PLI
    - application of the PL to the wind profiles.
- This study revealed the difficulty in modeling wind profiles for low velocities, which should be addressed in future work.
  - The analysis of thermal and air pollution in urban areas is more relevant for low wind velocities, since that results in more serious events that cover a larger fraction of people's daily lives.

Thank you for your attention!
and *Questions??*

Acknowledgments:
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Variations in the power-law index with stability and height for wind profiles in the urban boundary layer
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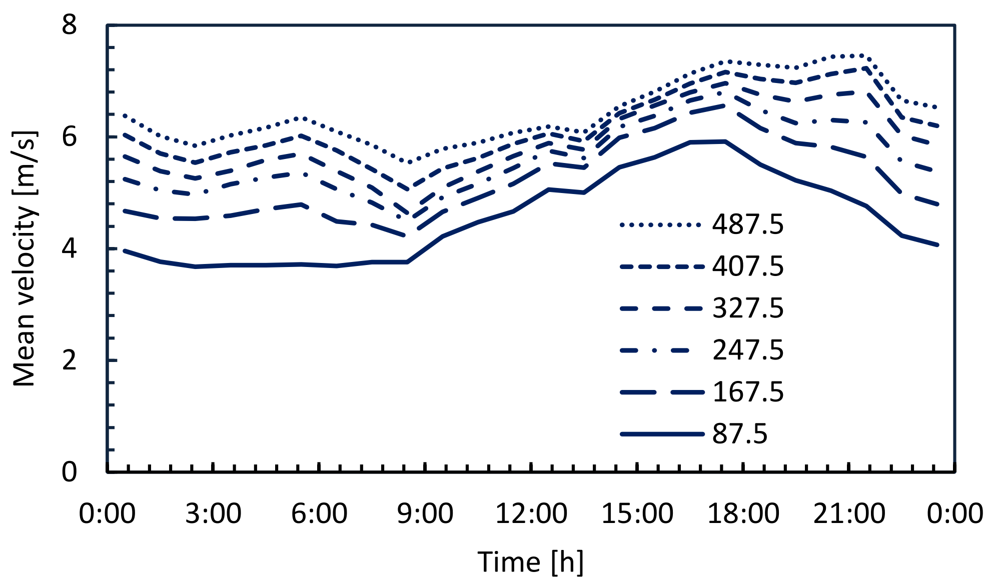
Diurnal variation in wind velocity

◻ Mean wind velocity during the observation

- 8AM – 18PM: Increase of velocity at every height
- 12AM – 15PM : Small velocity differences during heights



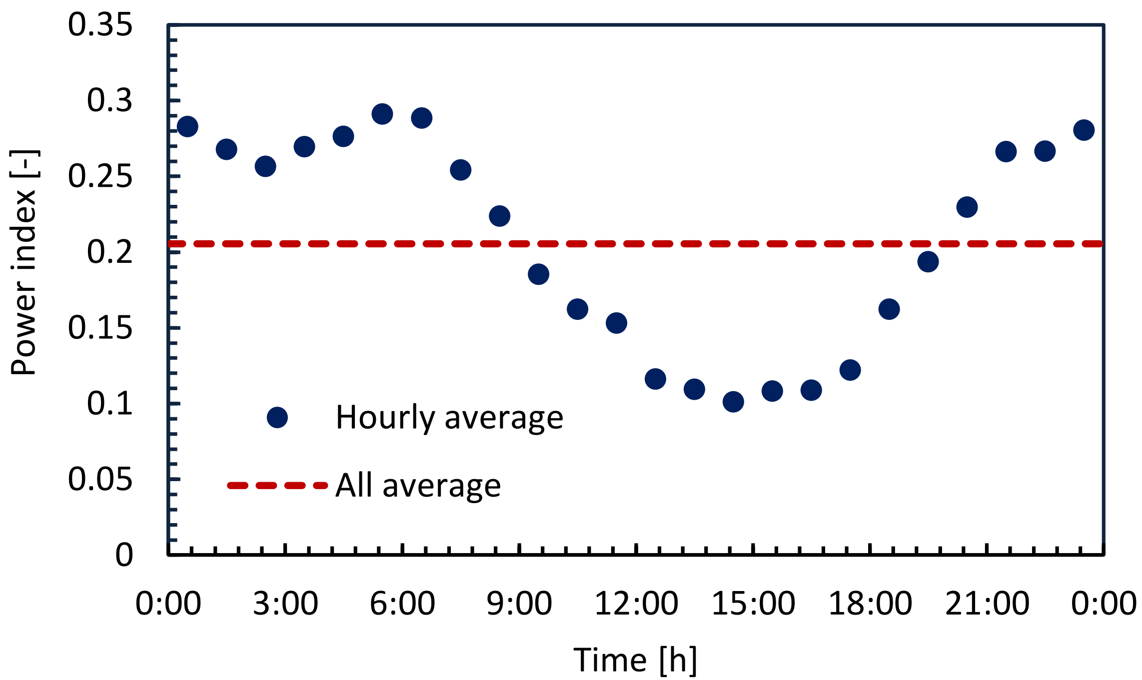
Mean diurnal variations of mean velocity at six measurement heights

(z = 87.5, 167.5, 247.5, 327.5, 407.5, 487.5 [m])

Power-law index of hourly averaged profiles

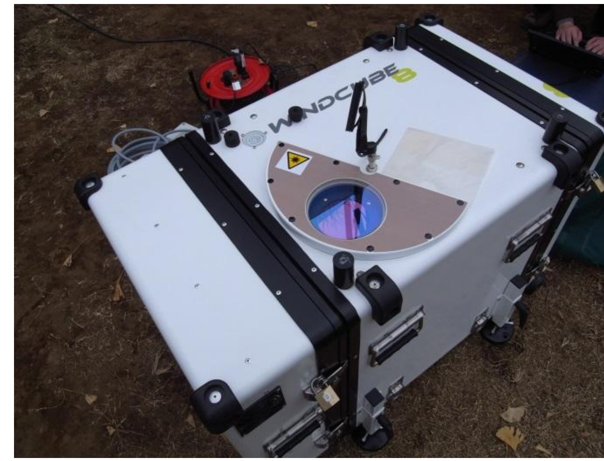
☐ PLIs hourly averaged wind profiles during the observation

- The PLI (α) changes from 0.1 (daytime) to 0.3 (night-time).
- Average PLI = 0.206



PLIs of hourly and daily averaged wind profiles

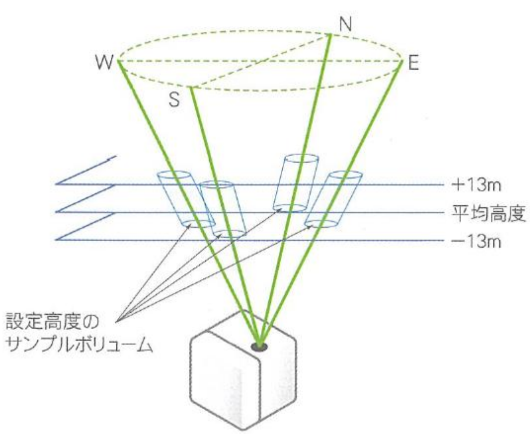
DLS: Doppler Lidar System

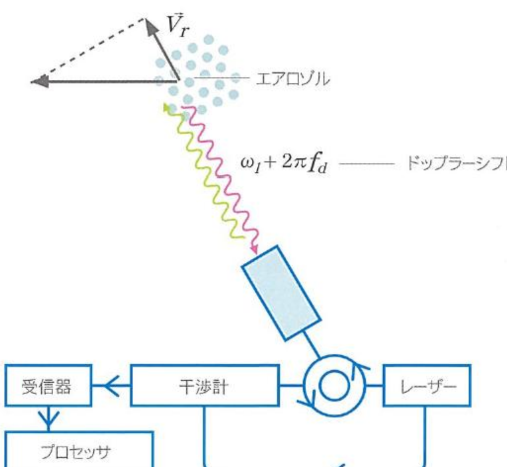


Lidar: Light Detection and Ranging

Windcube WLS8

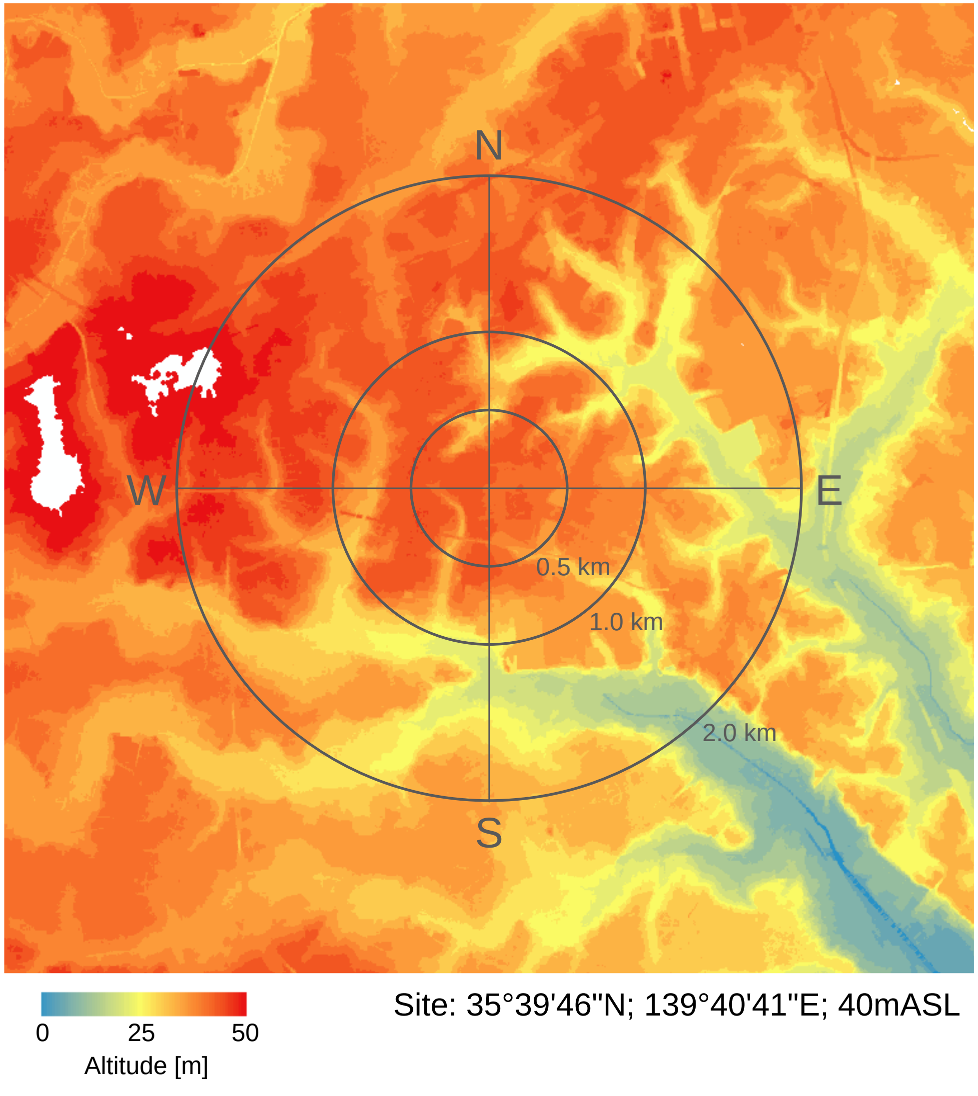
- Manufactured by Leosphere (France)
- Principle of measurement:
  1. Emission of pulse lasers (λ = 1.54 μm)
  2. Scattering of the laser by aerosols
  3. Measurement of velocity component in the line of sight using the Doppler shifts of the scattered light
  4. Calculation of 3D velocity components vector synthesis of 4 directions
- Measurement height: 40 - 500 m
- Minimum interval of height: 20 m
- Covered wind speed: 0 - 60 m/s
- Accuracy:
  - Wind direction: 1.5 °
  - Wind speed: 0.2 m/s
- Data output rate: every 10 seconds
- Size, Weight:
  940 x 740 x 640 mm, 90 kg





ドップラーヘテロダインライダーの原理

Altitude around the site



Site: 35°39'46"N; 139°40'41"E; 40mASL