WESC 2023
23 - 26 MAY | GLASGOW, UK

Experimental Results Of The Digitalization Of Wind Flow With LIDAR For Different Application: Met Mast Substitution, Urban Wind And Airborne

Wind Energy Science Conference 2023
23 – 26 May 2023
Glasgow, United Kingdom

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CEDER-CIEMAT (SPAIN)

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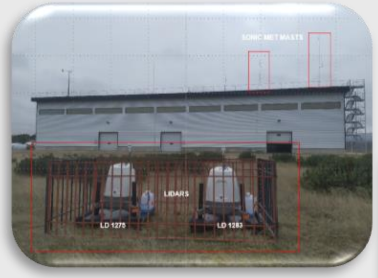
Centro de Desarrollo de Energías Renovables (**CEDER - CIEMAT**)



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CASE 1: TEST SITE CALIBRATION AND PPT

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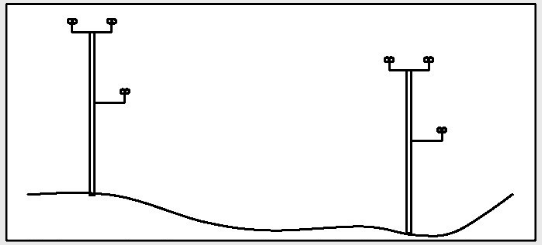
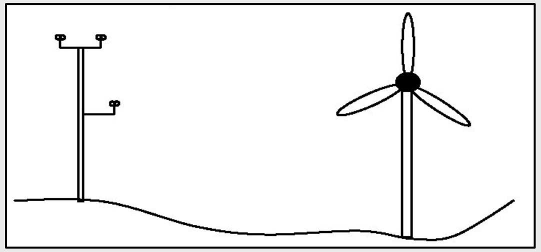
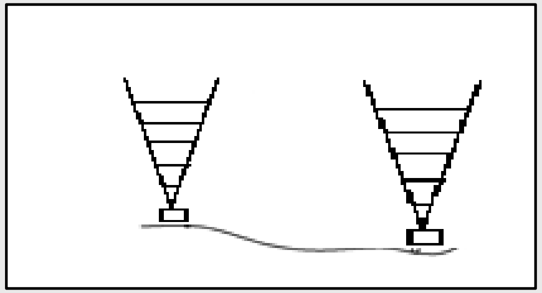
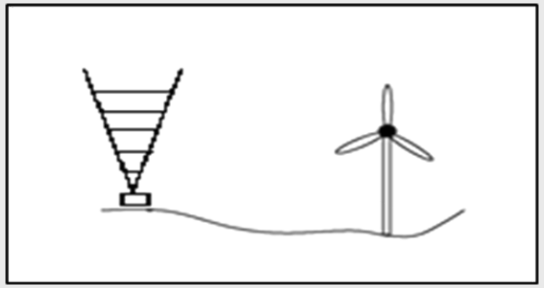
2 met mast





2 LIDARs





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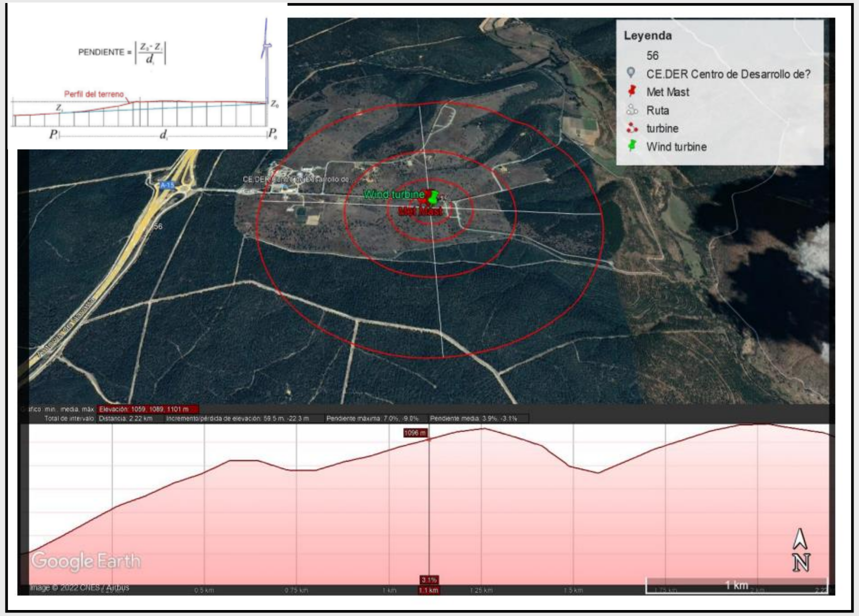
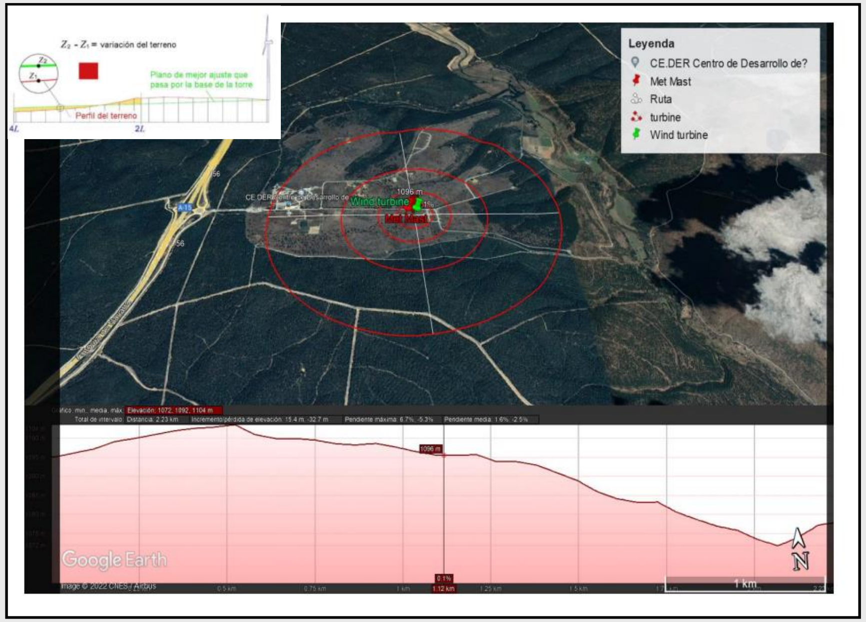
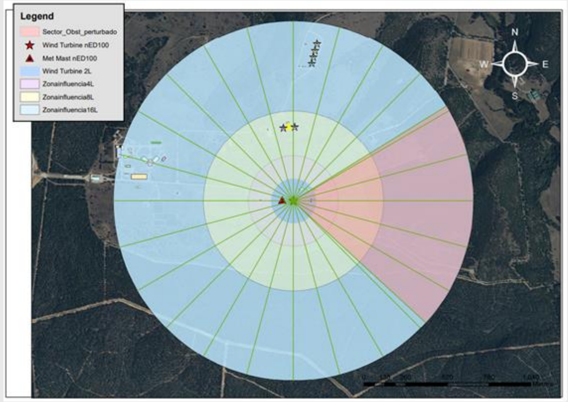
CASE 1: Assessment of obstacles and terrain

IEC 61400-12-1.Ed3: Wind energy generation systems – Part 12-1: Power performance measurements of electricity producing wind turbines

IEC 61400-12-5, Wind energy generation systems – Part 12-5: Power performance – *Assessment of obstacles and terrain* → Complex Terrain







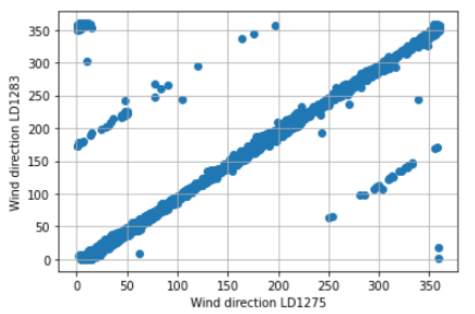
#CASE 1: Equipment and data filters

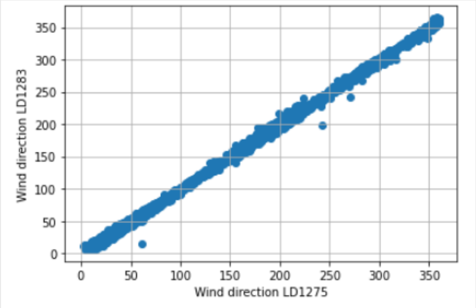
Equipment information

LIDAR	Information
Measurement period	24-03-2022 to 08-06-2022
2 LIDAR ZX 300	11 height: - 12m, 20m, 24m, 26m, 36m, 39m, 46m, 48m, 60m, 70m, 100m
Wind Turbine X (100 kW)	D= 24m, L= 70m (2.9D), H = 36 m

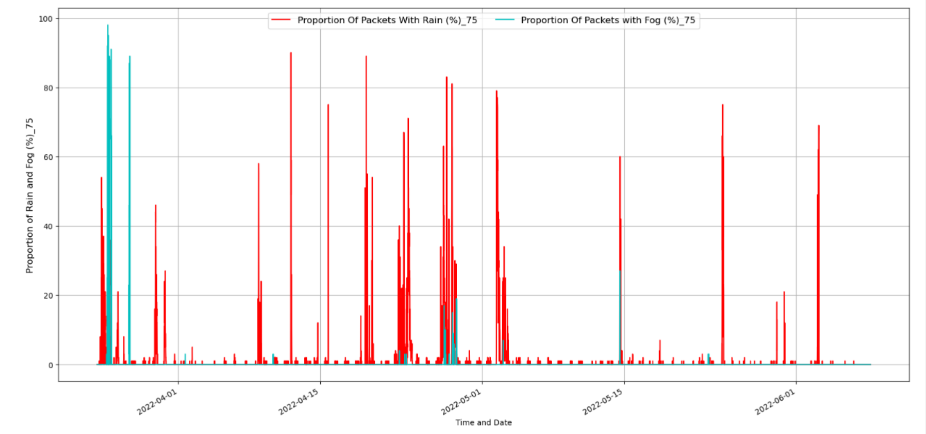
Filters data

Wind direction → Low wind speed → Disaligment





Fog and rain→ Low quality data



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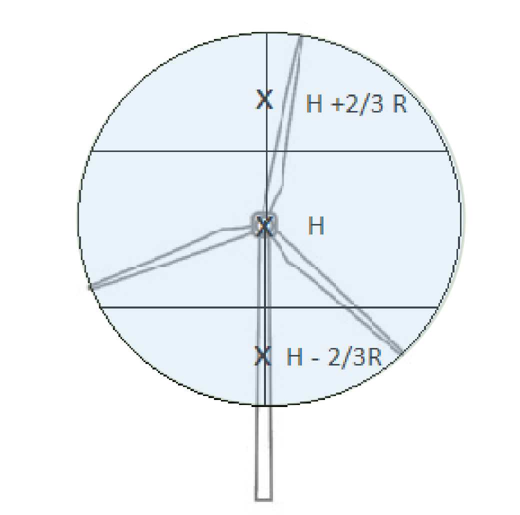
Case 1: REWS and Wind Shear

Vrews

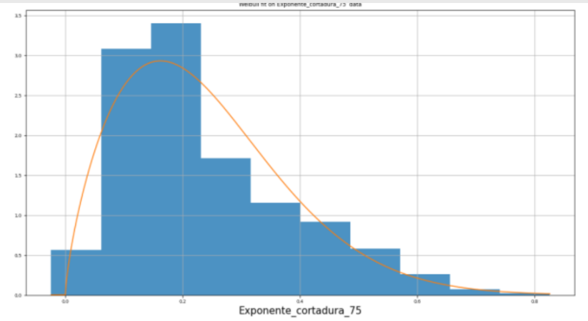
$$V_{eq} = \sqrt[3]{\left(\sum_{i=1}^{n_h} v_i^3 \frac{A_i}{A}\right)}$$



Wind shear

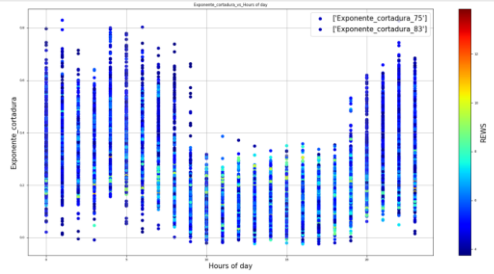
$$\alpha = \frac{\ln\left(\frac{v_{zi}}{v_H}\right)}{\ln\left(\frac{Z_i}{H}\right)}$$

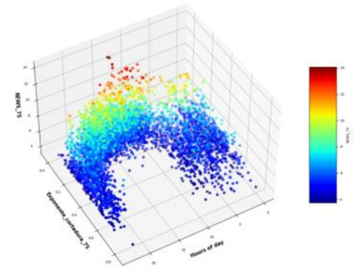
In case there are more levels, the shear exponent is calculated by means of a least squares adjustment.

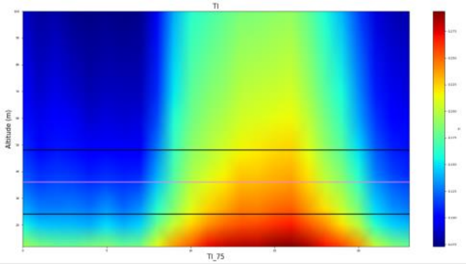


Diurnal cycle of atmospheric stability

At night, the atmosphere forms thermal layers (stable atmosphere). These layers suppress turbulence and result in variably high wind shear. During the day, the sun heats up the ground, introducing turbulent mixing which results in a more uniform wind speed profile (low wind shear) and higher turbulence.







#Case 1: Significant wind shear and Method 1

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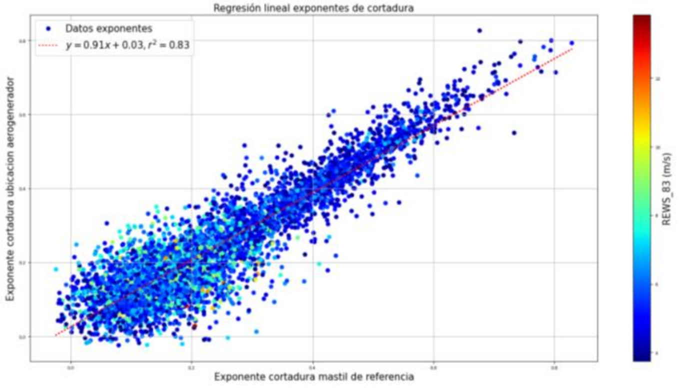
Check % of wind shear: **α > 0.25 and 25% data**

Significant Wind Shear

Wind shear exponent	Data number	Porcentage (%)
(-0.025, 0.25]	3507	64.04
(0.25, 1.0]	1969	35.96

Verify correlation of wind shear at wind turbine and reference LIDAR locations



Method 1: Bins of wind direction and wind shear

Flow corrections at site calibration (wind speed ratio)														
	Wind Direction Bin (º)													
	10		20		30		40		210		270		280	
Wind Shear Exponent	WS ratio	Nº data	WS ratio	Nº data	WS ratio	Nº data	WS ratio	Nº data	WS ratio	Nº data	WS ratio	Nº data	WS ratio	Nº data
0	0.980	4	0.969	7	0.981	10	0.980	7	1.022	1	1.000	9	0.996	6
0.05	0.992	20	0.991	25	1.008	24	0.967	42	0.978	15	0.995	26	0.995	28
0.10	0.998	45	0.986	52	0.988	57	0.988	61	0.986	38	0.995	73	0.993	83
0.15	0.998	37	0.986	70	0.994	57	0.991	73	0.992	39	0.992	77	0.995	92
0.20	1.015	26	0.992	43	1.001	53	0.995	43	0.994	70	0.994	40	0.998	68
0.25	1.000	23	0.987	31	1.000	36	1.022	24	1.005	37	0.995	30	0.999	55
0.30	1.004	6	0.981	17	1.002	28	0.996	13	0.990	16	0.999	23	0.998	44
0.35	0.982	9	0.989	10	0.999	23	1.009	8	1.017	12	1.001	19	1.002	48
0.40	0.992	4	0.996	8	0.994	14	1.011	9	1.001	10	1.000	15	1.002	42
0.45	0.983	5	0.990	5	0.987	7	0.994	5	1.010	7	1.007	14	0.999	35
0.50		1	0.962	3	0.983	5	1.011	8	1.018	4	1.008	12	1.003	9
0.55		0		2	1.001	3	0.984	10	1.004	4	1.009	9	0.995	17
0.60		2		2		1		1		0		1	0.977	4

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#Case 1: Method 1 – Quality checks

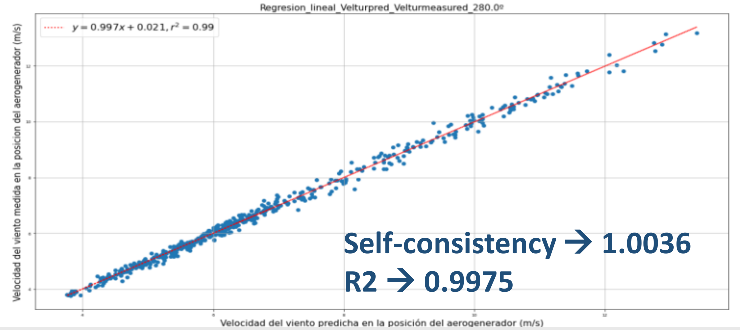
Assess significance of shear

a) self–consistency parameter $= V_{Turb_{predicted}} / V_{Turb\_measured}$ [0.98 y 1.02]

b) linear regression of Vtur_predicted vs. Vtur_measured R2 > 0.95

Linear regression of wind turbine location vs. reference LIDAR for 280° bin, post-filtering

$$\mathbf{V_{Turb\_predicted}} = \mathbf{F(WD, \alpha) * V_{ref\_measured}}$$

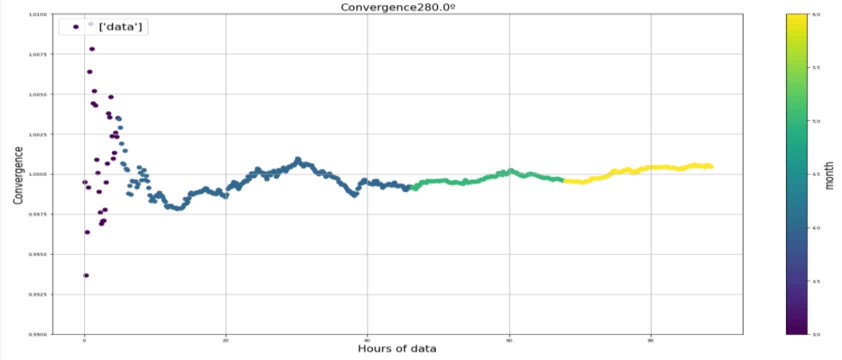


Completion criteria for wind direction

- At least 144 data per bin (24 hours of data)
- At least 6 hours > 8m/s and 6 hours < 8 m/s (36 data)
- At least3 data point per bin Wind Direction/Wind Shear exp.

Convergence check

The cumulative averages should be seen to converge to within 0,5 % of the final average within the larger of 16 h of data or 25 % of the total number of data points in that bin.



Change in correction between adjacent wind direction bins

Bin centre	Magnitude of change between bins (left)	Magnitude of change between bins (right)	Additional standard uncertainty (%)
10	0.992	0.999	0% (within limit)
20	1.011	1.014	0%
30	1.002	0.993	0%
40	1.002	1.007	0%
210	1.006	1.014	0%
270	1.001	1.002	0%
280	1.005	1.001	0%

Case 1: Statistical Uncertainty

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Uncertainty → k-fold cross validation

The total category A uncertainty is the square root of the sum of the squares of the uncertainty calculated for each fold divided by the square root of k

$$sc = \sqrt{\frac{\sum_{i=1}^{k} s_{sc,i}^{2}}{k}}$$

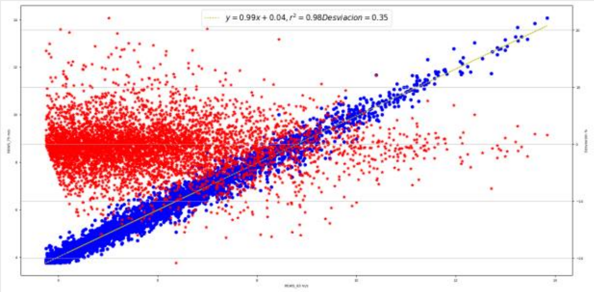
Category A uncertainty for REWS LIDAR

```
La IncertidumbreA de la calibración es: 0.000642033367000386
```

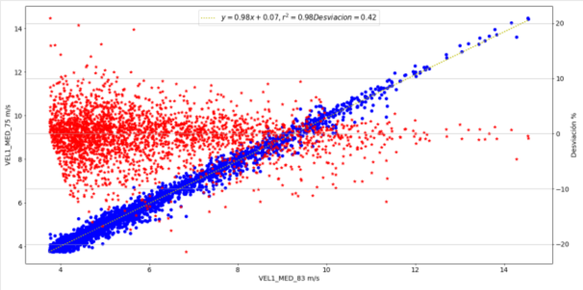
Category A uncertainty for Hub Height LIDAR

```
La IncertidumbreA de la calibración es: 0.0012293226793015518
```

LIDAR



CUP ANEMOMETER



- Linear regression between LIDARs R2 = 0.98
- Linear regession between cup anemometers R2 = 0.98
- Bias cup anemometer> Bias LIDARs

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#Case 1: Power Performance Test

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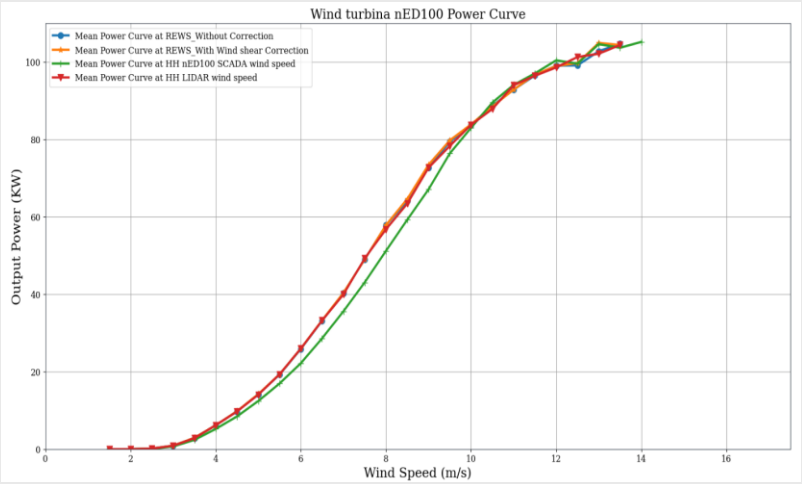
Power Performance Test with Test Site Calibration Correction

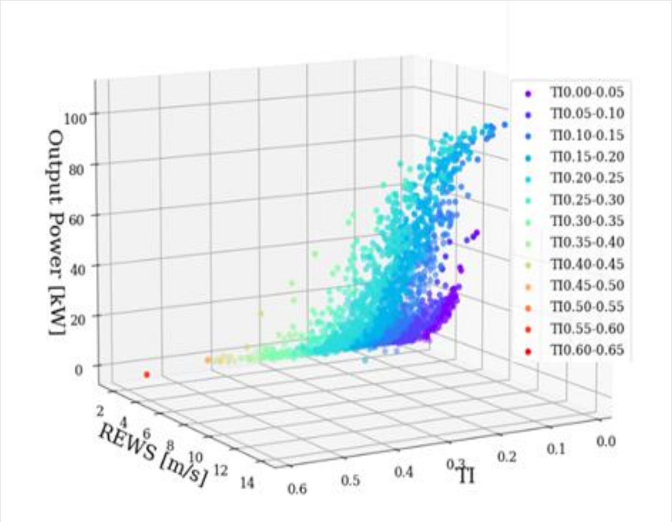
$$V_{eq} = \sqrt[3]{\left(\sum_{i=1}^{n_h} v_i^3 \frac{A_i}{A}\right)}$$

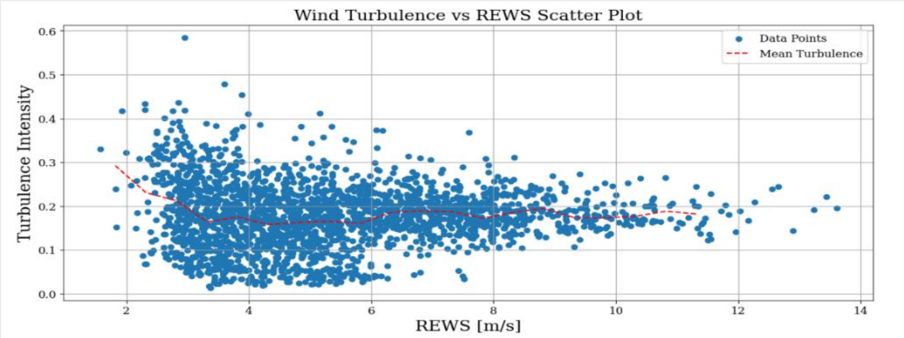
$$V_n = V_{10min}\left(\frac{\rho_{10min}}{\rho_o}\right)$$

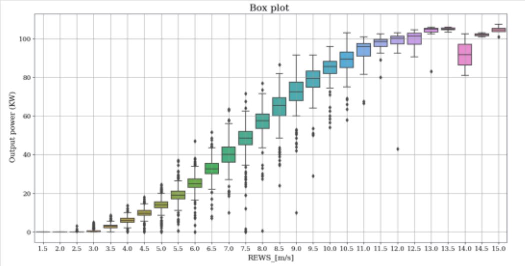
$$V_i = \frac{1}{N_i}\sum_{j=1}^{N_i} V_{n.i,j}$$

$$P_i = \frac{1}{N_i}\sum_{j=1}^{N_i} P_{n.i,j}$$









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Case 2: SONIC ANEMOMETERS AND LIDAR

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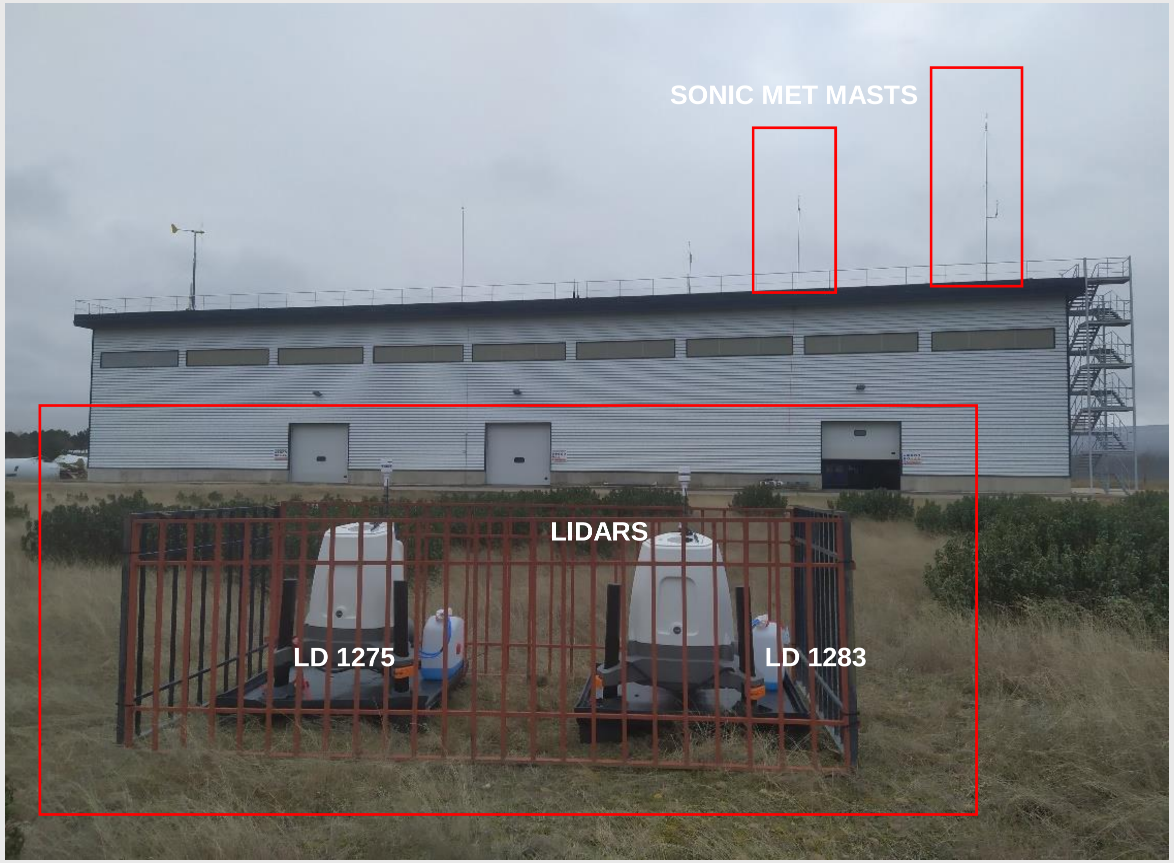
Equipment around LECA building (building Height 11.40 m)



Sonic anemometer met mast on the roof 10 m, with 2 Sonic anemometers at 5 m and at 10 m on the roof.

Sonic anemometer met mast on the roof 5 m

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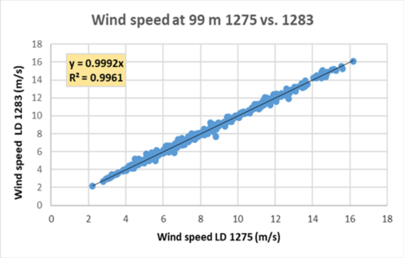
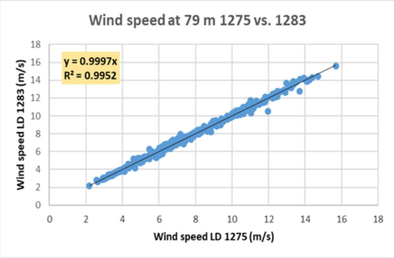
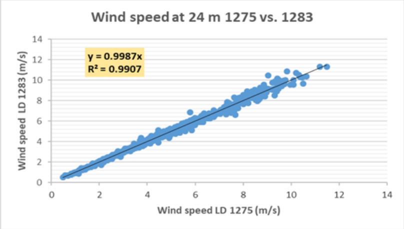
Case 2: Verification of measurement

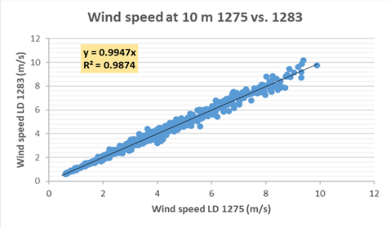
Several comparisons have been made:

- between LIDAR vs. LIDAR
- between sonic vs. sonic anemometers
- Between LIDAR vs. sonic anemometers

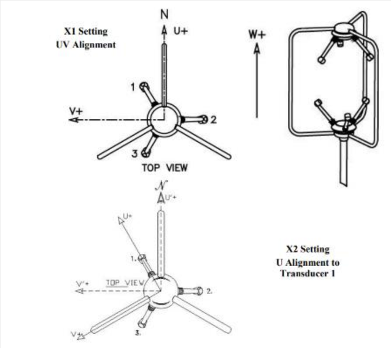






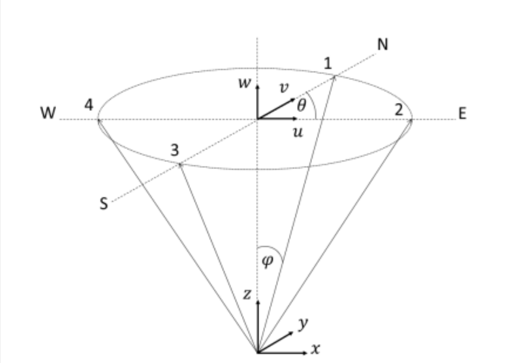


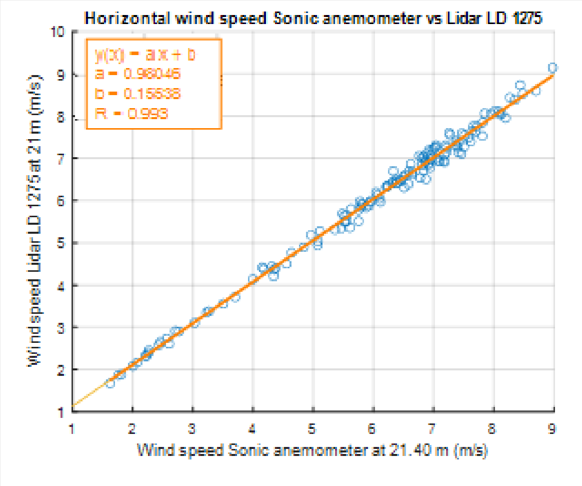
Relationship between Sonic anemometer and LIDAR coordenates systems

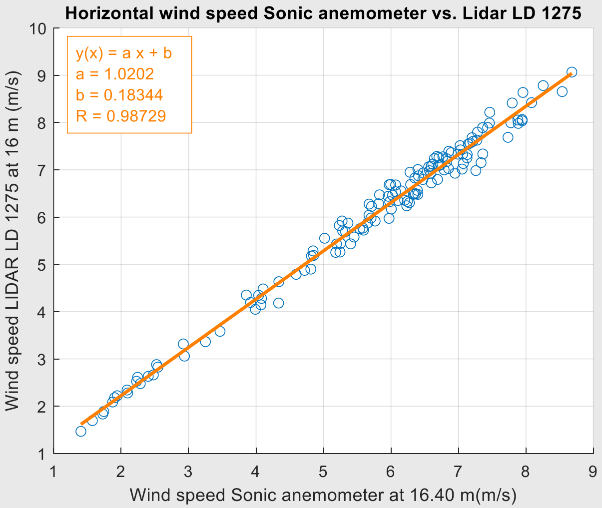


$U_{sonic} = V_{lidar}$

$U_{lida}r = - V_{sonic}$







Case 2: Test site locations

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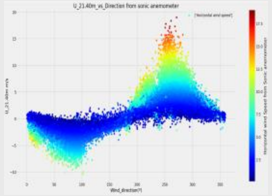
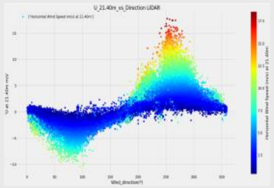
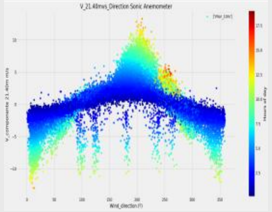
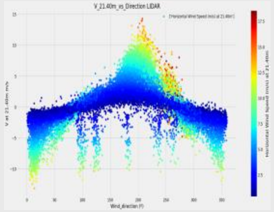
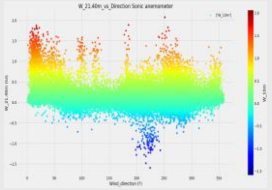
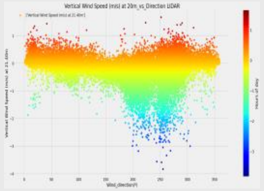
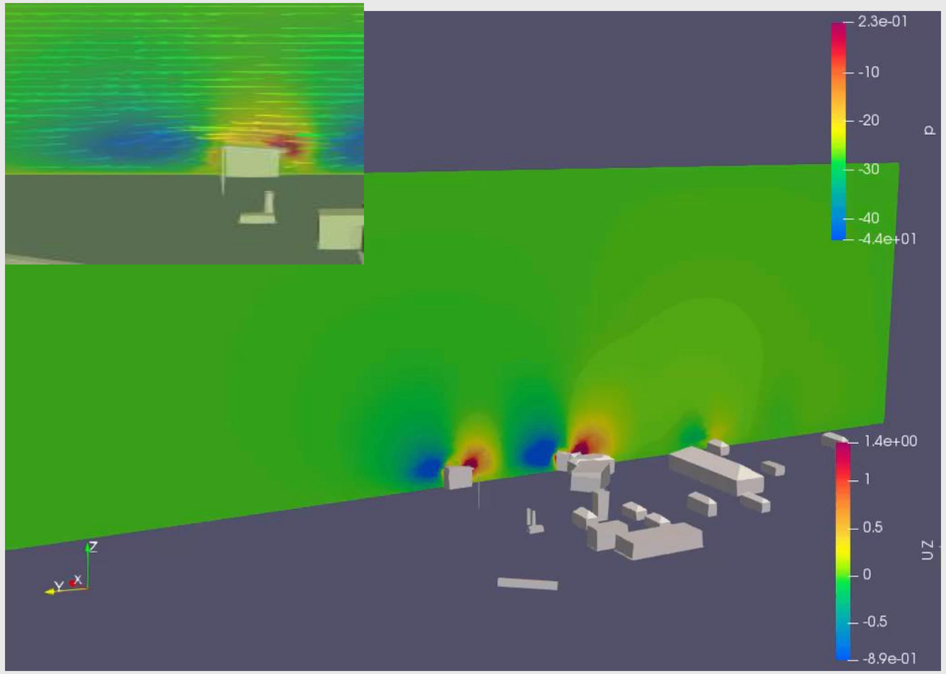
Case 2: Component of wind speed

- Behaviour of wind flow around building

Wind speed Components	Sonic anemometer	LIDAR
U (m/s)		
V (m/s)		
W (m/s)		

OpenFOAM → Wind speed component behaviour



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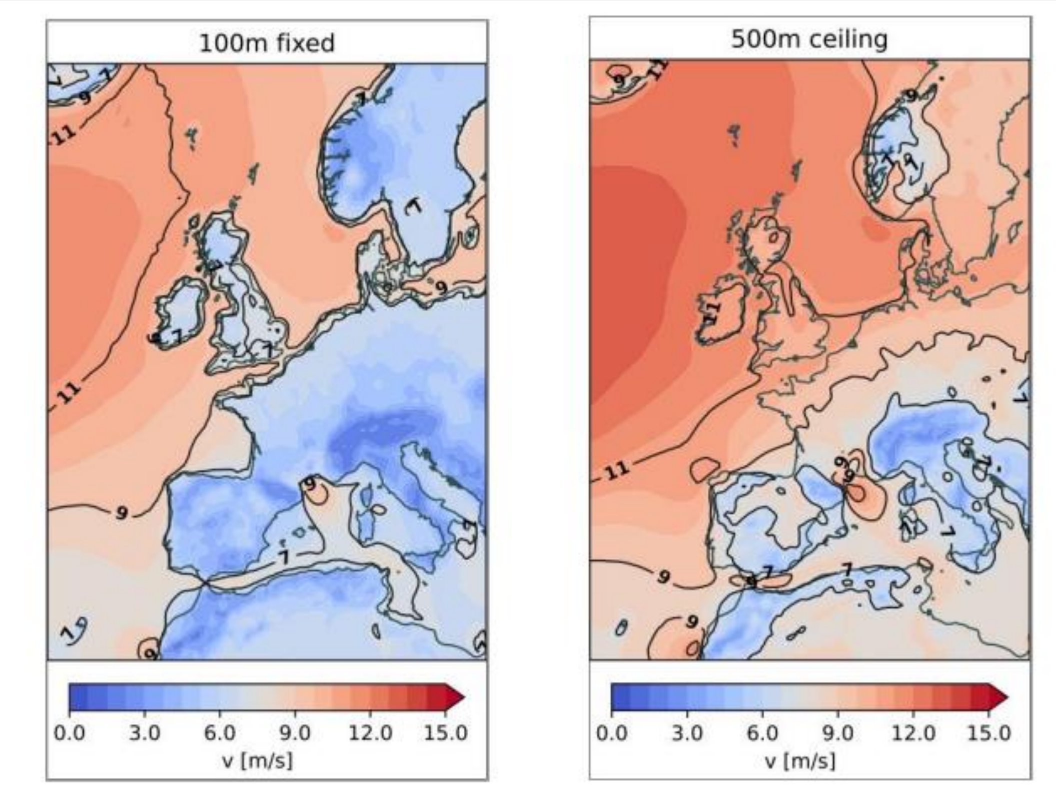
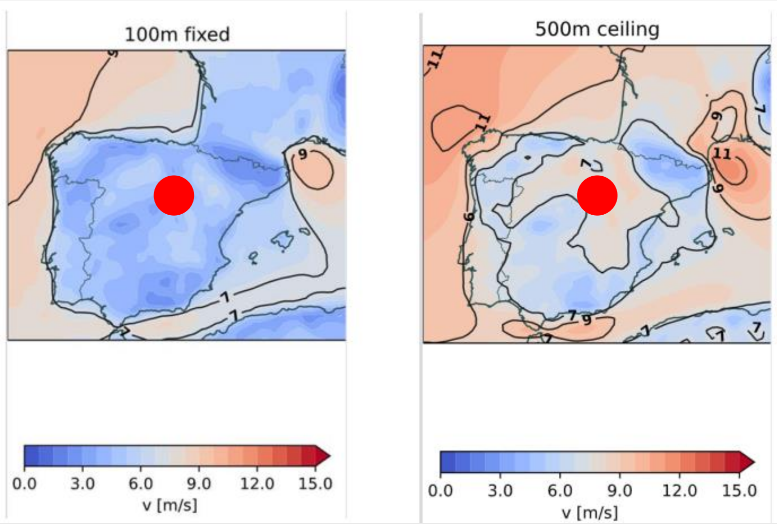
Case 3: LIDARs WORKING WITH AIRBORNES

Wind speed resource ERA5



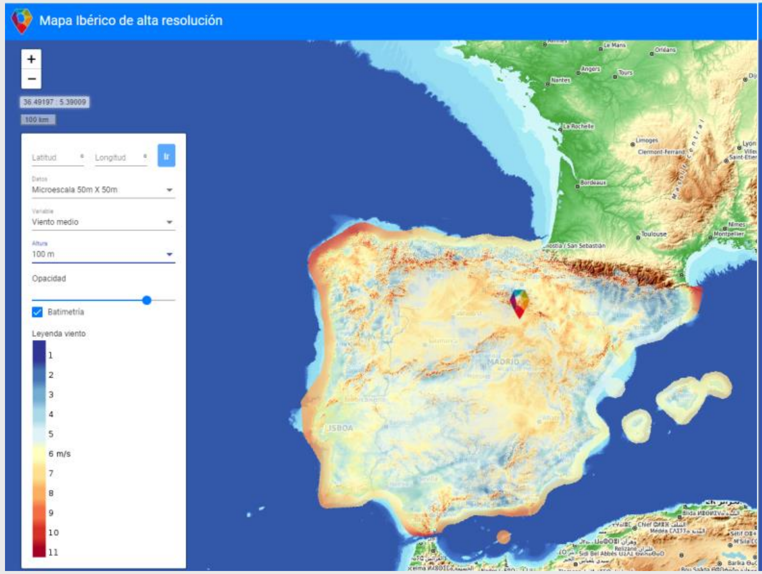
Source: Bechtle et. al., wind data: ERA5

Red color:
WS > 7.5 m/s → Excelent conditions

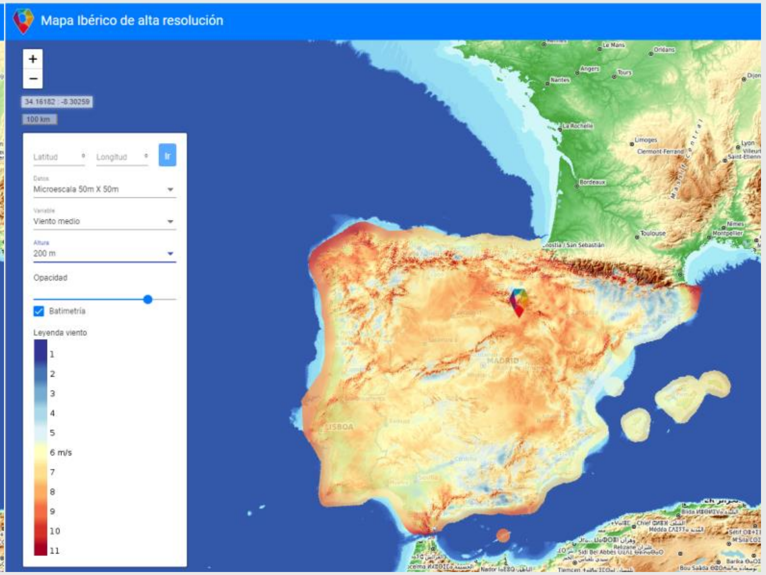


Case 3: Wind Resource in CEDER

Wind speed resource “Mapa Ibérico”

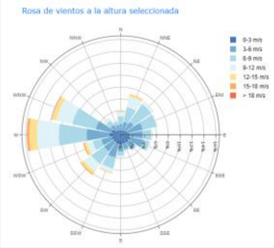


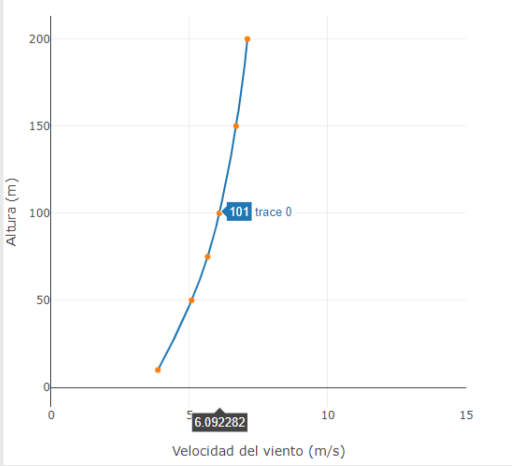
100 m



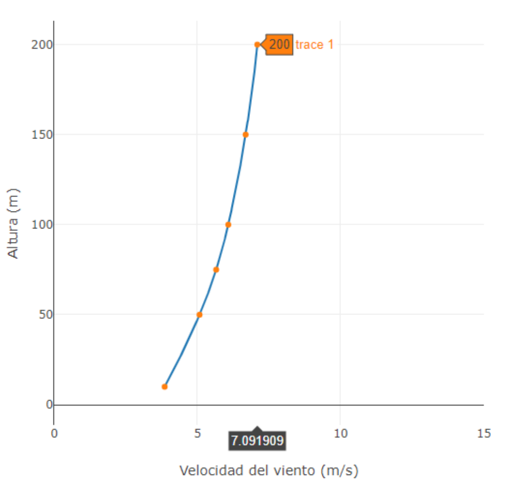
200 m

100m





200m



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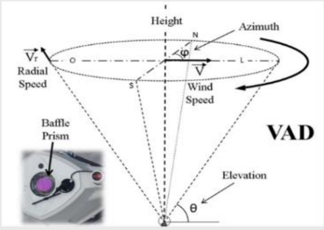
Case 3: LIDAR location at CEDER-CIEMAT

LIDAR location at CEDER-CIEMAT→ Flight Test Center

ZX 300 LIDAR → VAD Scanner



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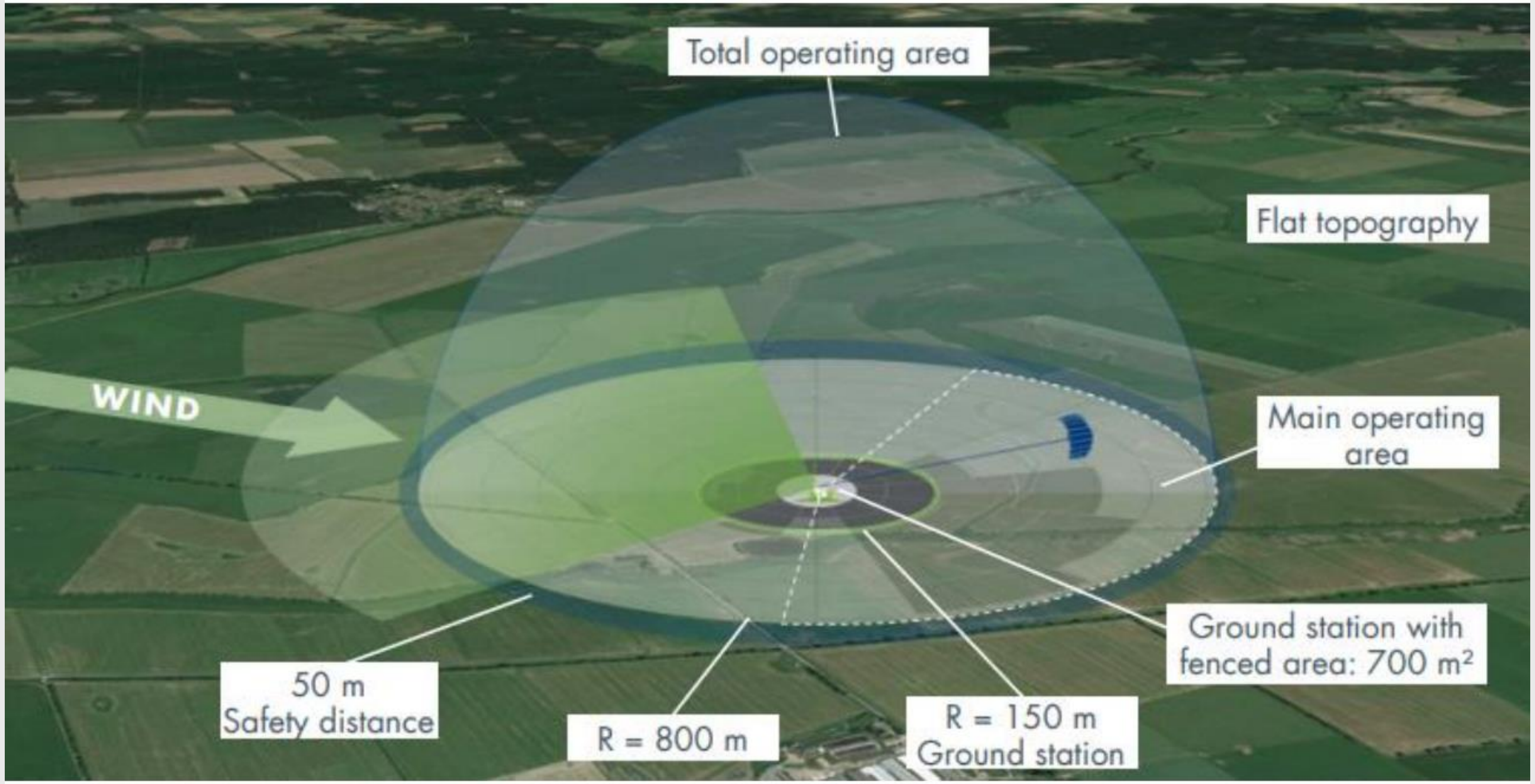
Case 3: AWE Site requeriments

Flight Test Center requeriments



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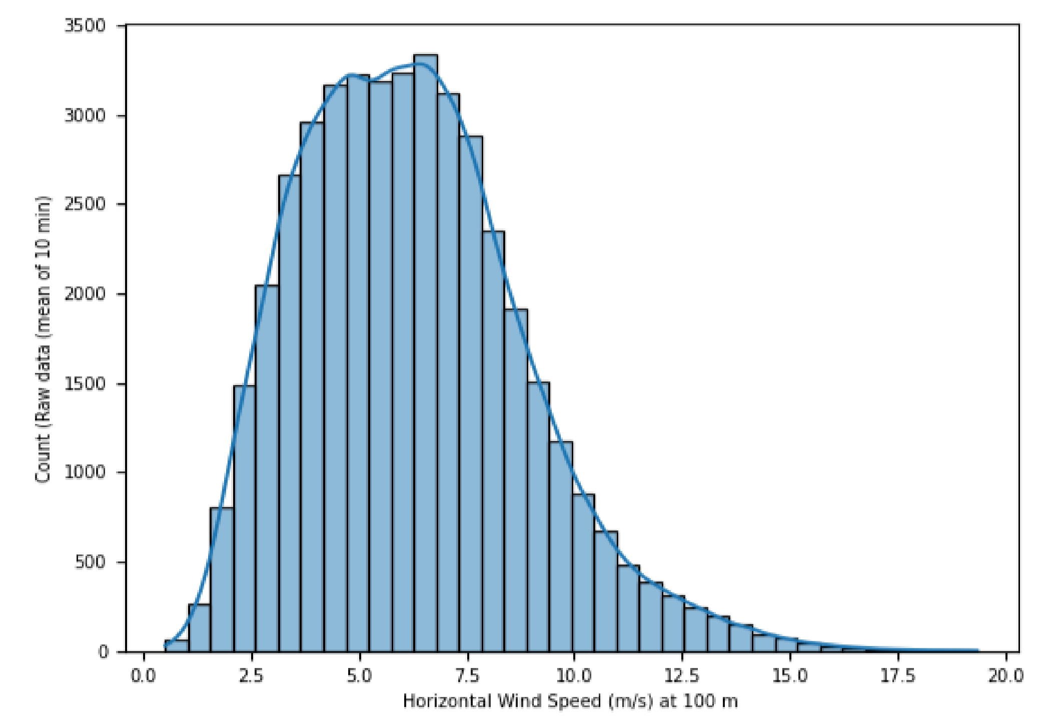
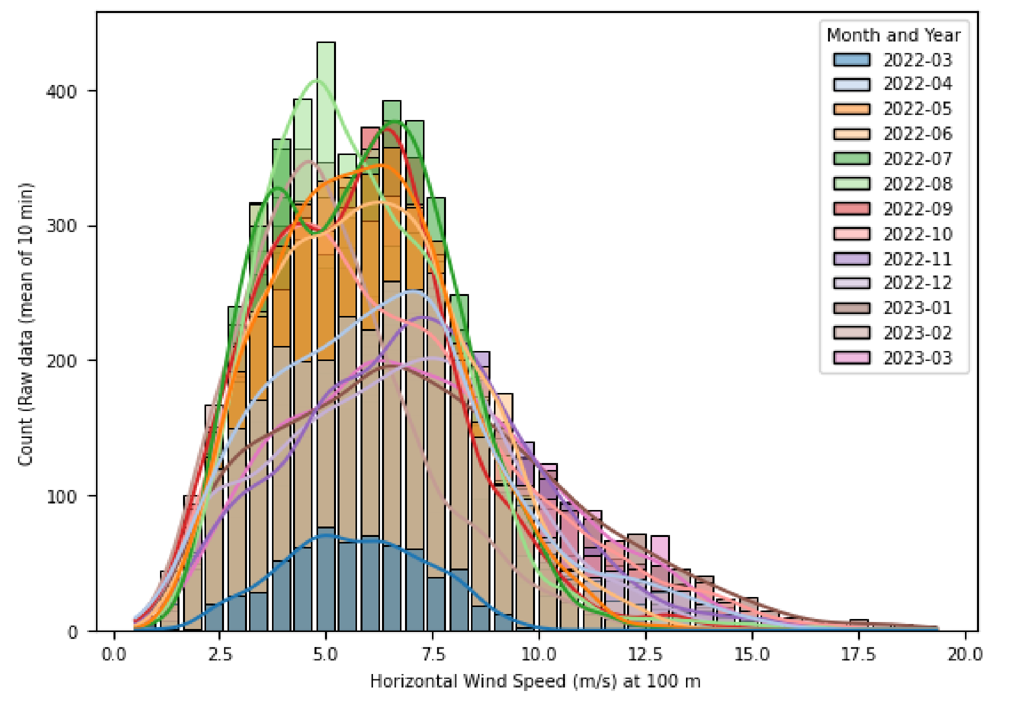
Case 3: LIDARs measurement resources at CEDER

Total Wind Speed distribution at 100 m

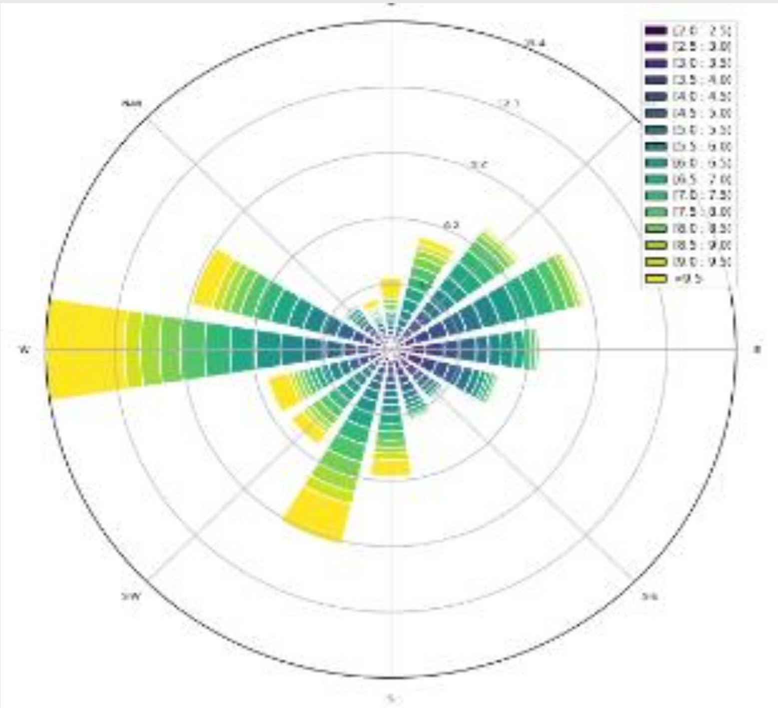


Wind Speed distribution by month at 100 m

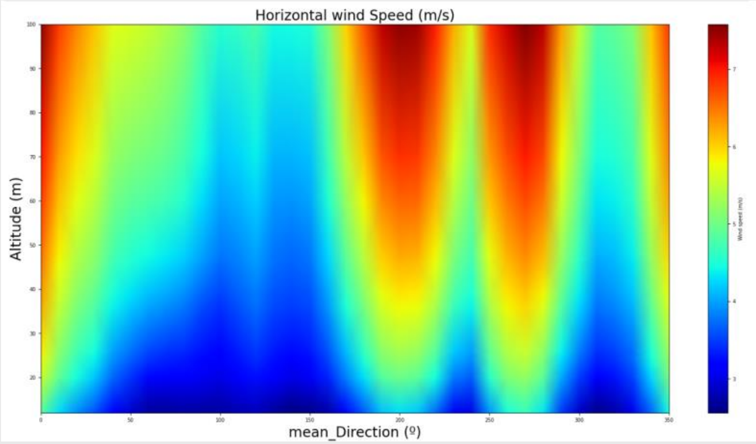


Case 3: LIDARs measurement resources at CEDER

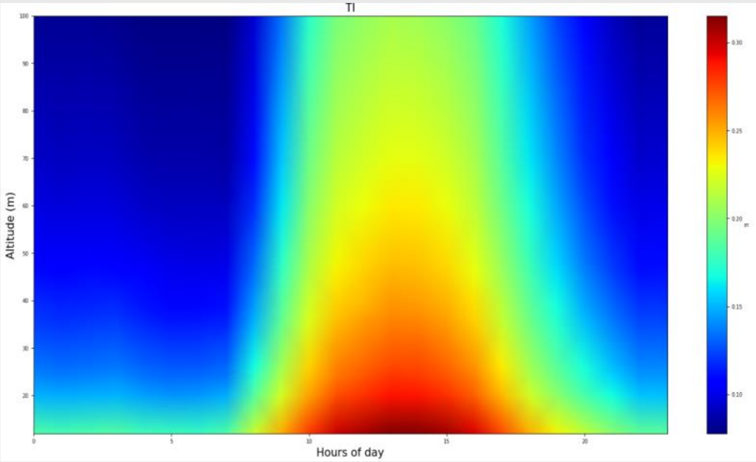
Wind rose at 100 m



Horizontal wind speed in relationship with wind direction for all height



Turbulence Intensity in relationship with hours of day for all height



Case 3: LIDARs measurement resources at CEDER

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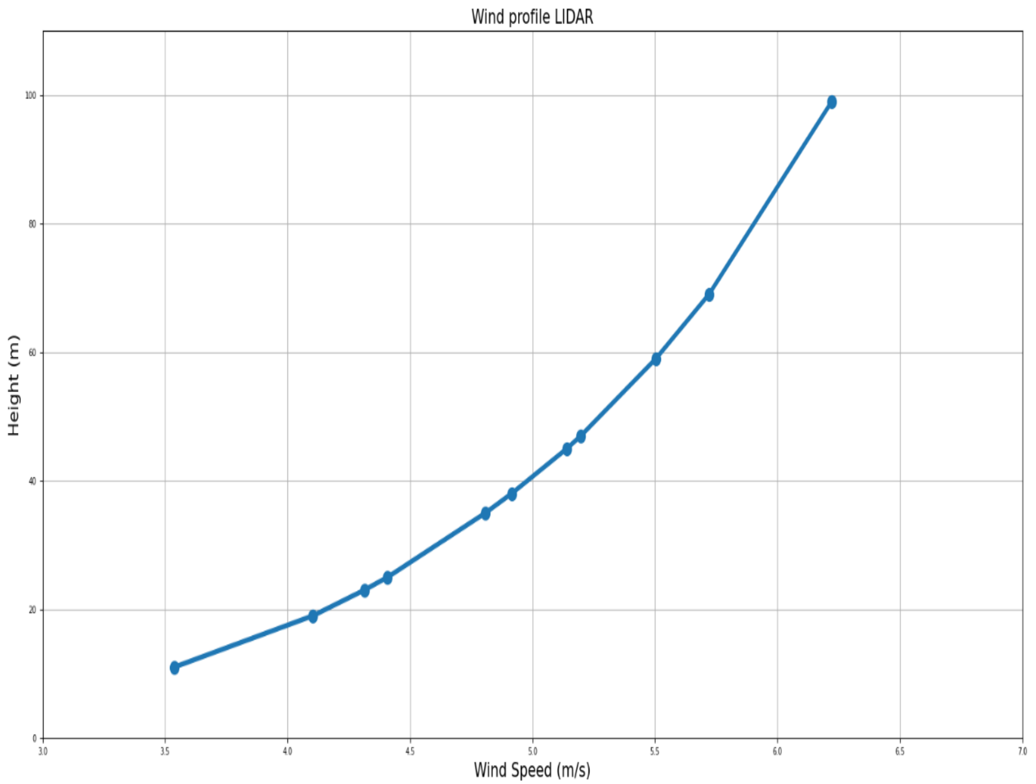
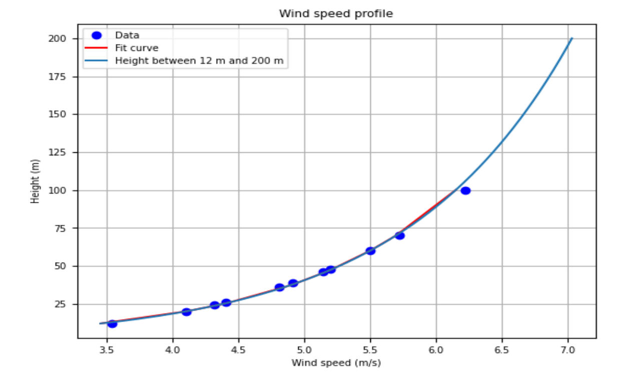
Wind profile until 100 m

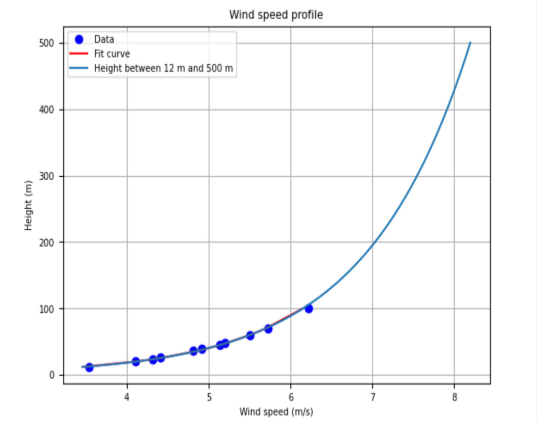


Wind profile fit until 200m



Von Karman coeficient: 0.4
Rugosity: 0.7958893027492805
Friction wind speed: 0.5091386318688714
u2 [200 m] m/s: 7.034529863944766

Wind profile fit until 500m



Von Karman coeficient: 0.4
Rugosity: 0.7958893027492805
Friction wind speed: 0.5091386318688714
u2 [500 m] m/s: 8.200827387996103

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VERSATILITY OF LIDAR

LIDAR wind measurement devices are highly versatile tools used in a wide range of ground-based applications, providing accurate and detailed real-time wind measurements.

The three examples presented in this presentation illustrate the significance of introducing new technologies in wind resource measurement.

The versatility of LIDAR in wind resource measurement is that these devices can be used in both open-field and peri-urban applications. This can help optimize the design of many projects.

THANKS FOR YOUR ATTENTION

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