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Insights into wind turbine reflectivity and radar cross-section (RCS) and their variability using X-band weather radar observations

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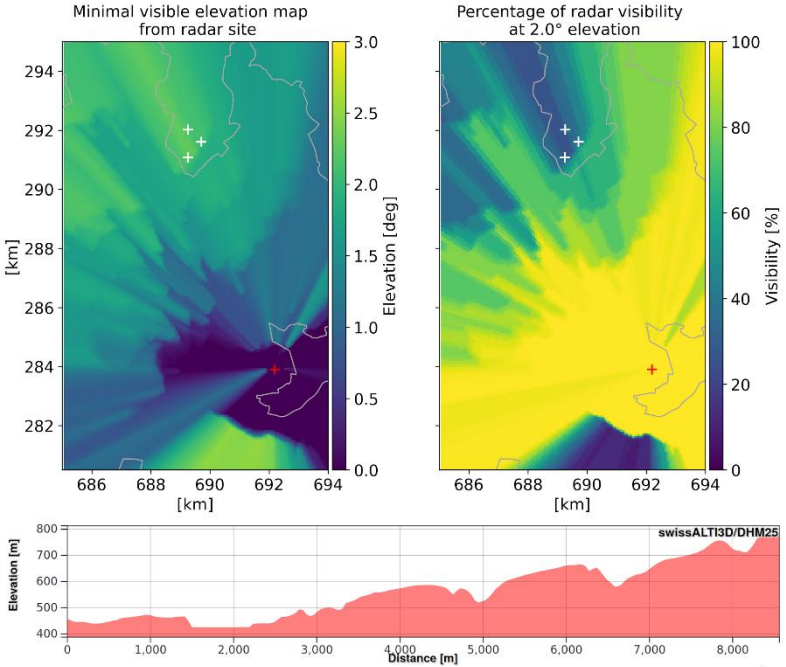
Objectives

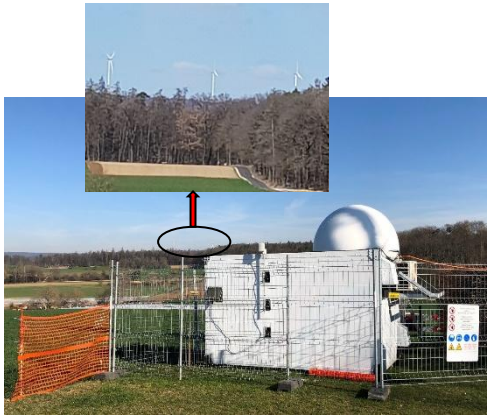
- In general, to better understand the effects of large, moving scatterers like wind turbines on radar returns

- Quantify the most intense radar returns of wind turbines from two field campaigns near Schaffhausen (2019 / 2020)

- Find relations with rotor speed, nacelle position and blade angle of the wind turbines

Measurement site and visibility





	Distance [km]	Azimuth [deg]	Elevation [deg]
DX50-WT1	**7.7**	338	2.1
DX50-WT2	**8.1**	342	2.0
DX50-WT3	**8.6**	340	2.0

X-band radar and WT characteristics

Meteor 50DX

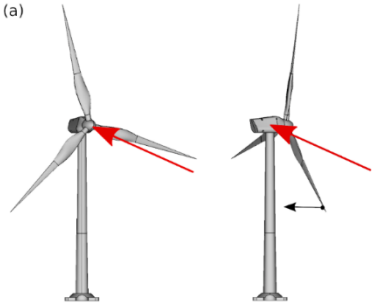
Frequency	9480 MHz
Transmitter type	Coaxial magnetron
Nominal peak transmit power	75 kW (half for each channel)
Dual-polarization mode	Simultaneous H / V
Receiver linearity	90 dB ± 0.5 dB
3 dB beam width	1.2°
Radome	Yes, screwed by metallic joints
Elevation scan range	-1° to 181°
Azimuth scan range	0° to 360°
Pointing accuracy	± 0.1°
Minimum detectable signal	-112 dB (0.5 µs pulse)

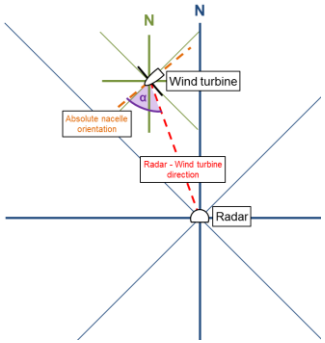
Upgrade to **seamless radome** in June 2019

Wind turbine

Turbine type	Nordex SE N131/3300
Rated power	3300 kW
Cut-in wind speed	3 m/s
Cut-out wind speed	20 m/s
Rotor diameter	131 m
Hub height	134 m
Total height	199.5 m
Rated rotational speed	10.9 rpm
Tip speed	74.8 m/s

Wind conditions and WT orientation/rotation

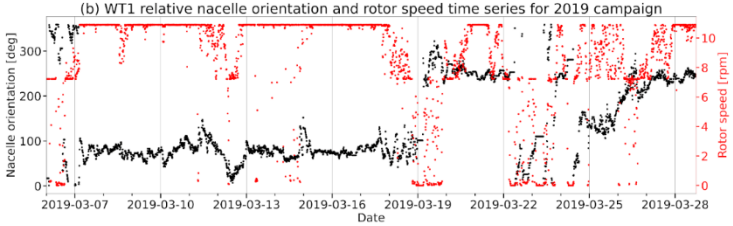


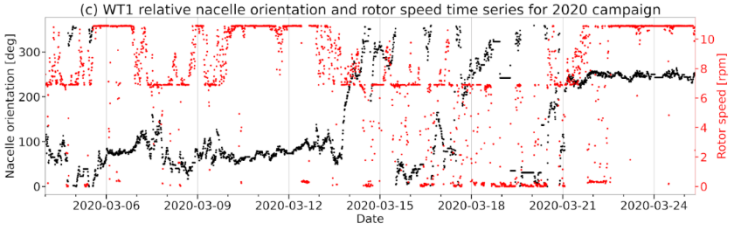


Convention:

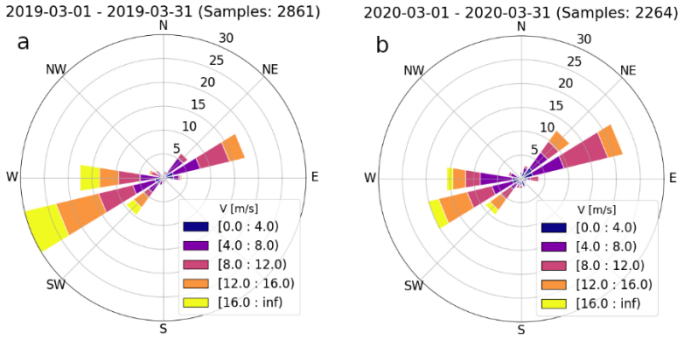
0° → Facing towards radar

180° → Facing away from radar

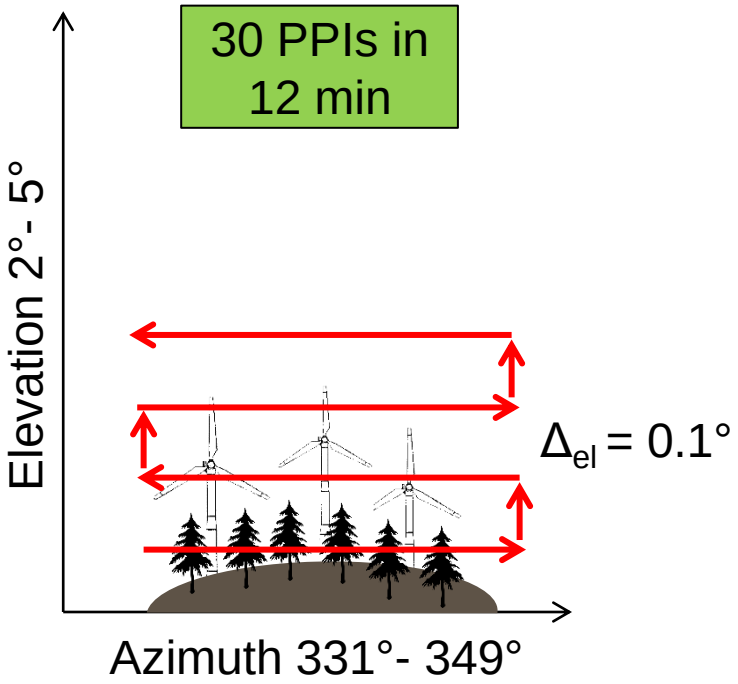


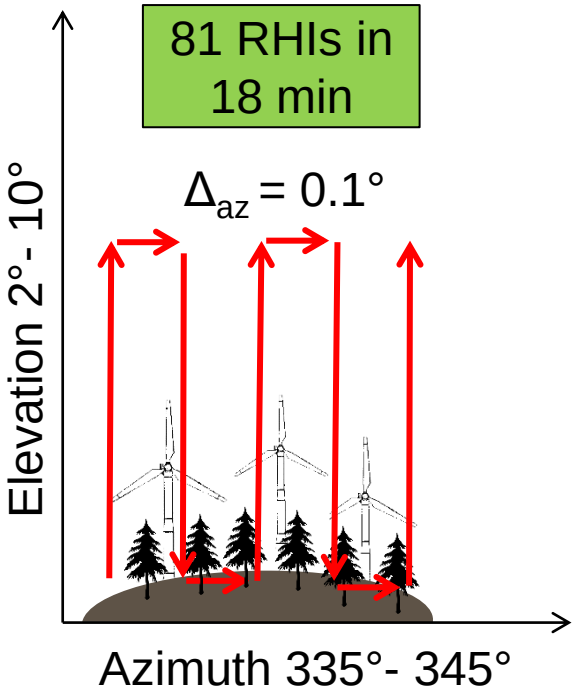


Wind profiler observations

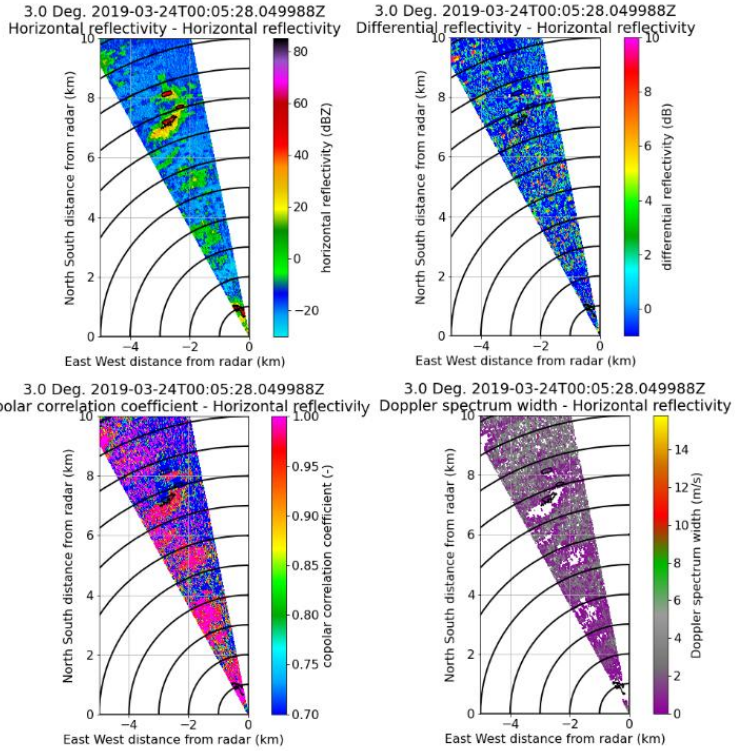


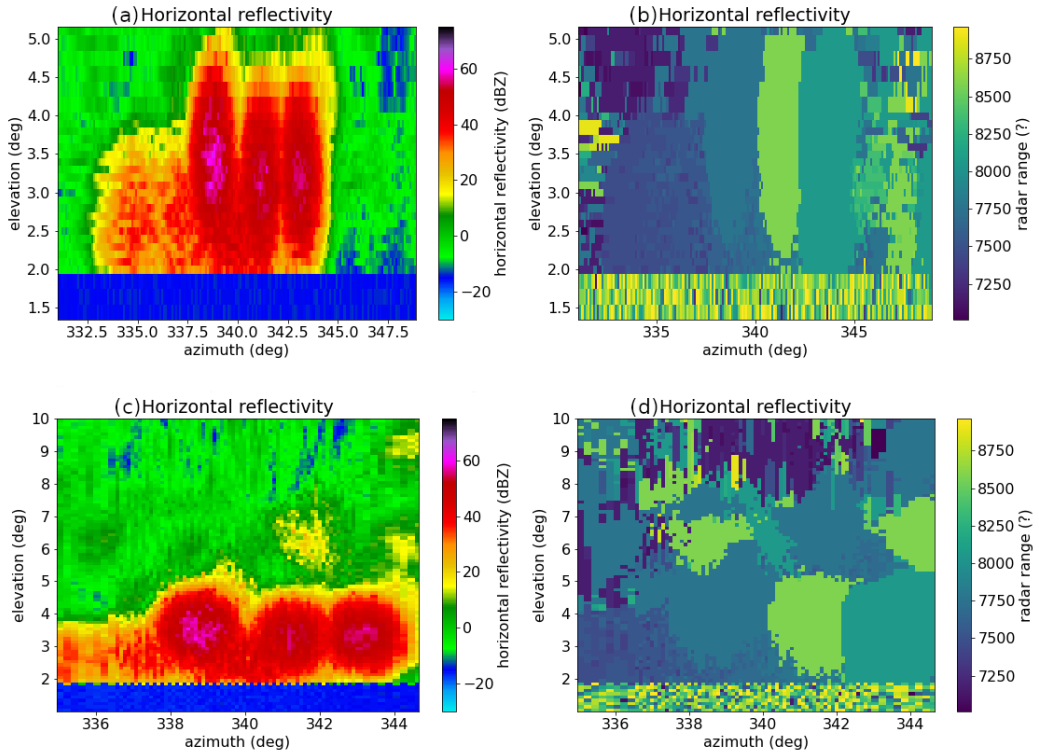
Scanning strategy (2019)



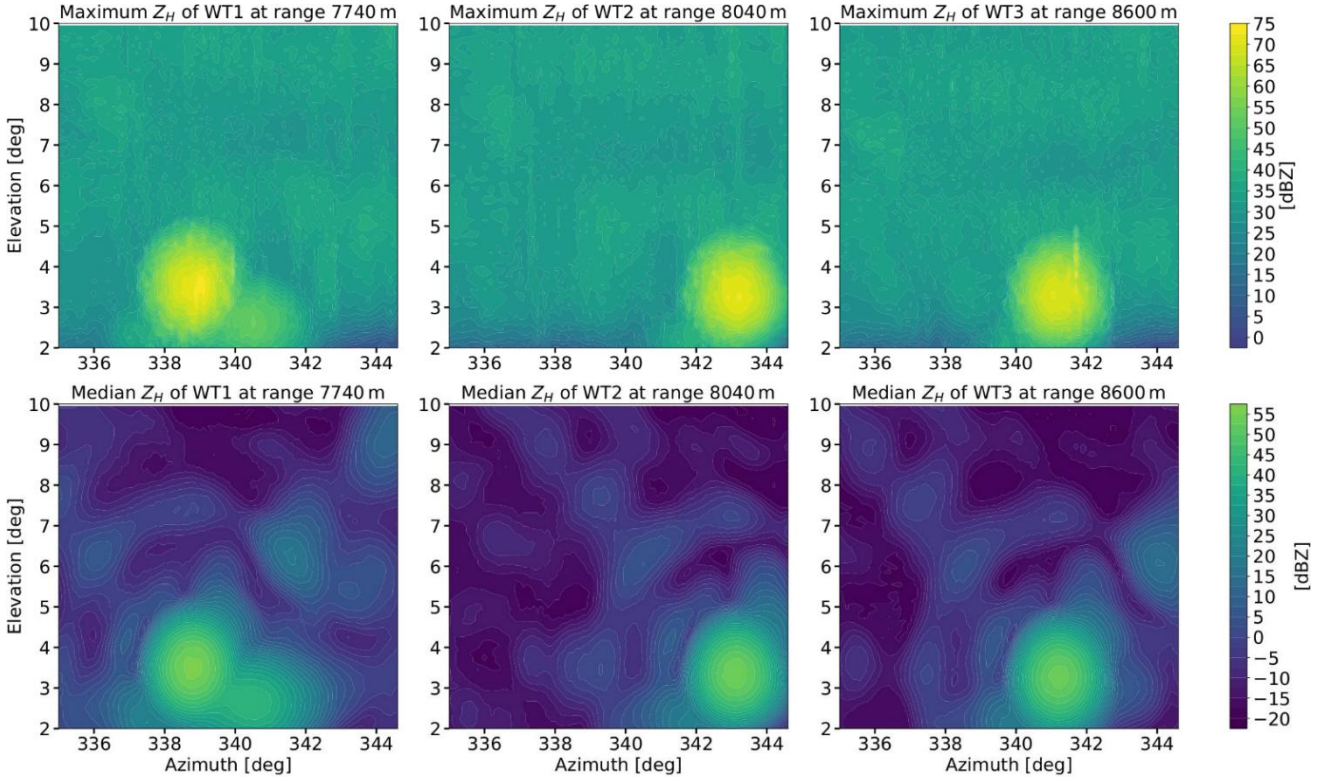


How data look like 2019

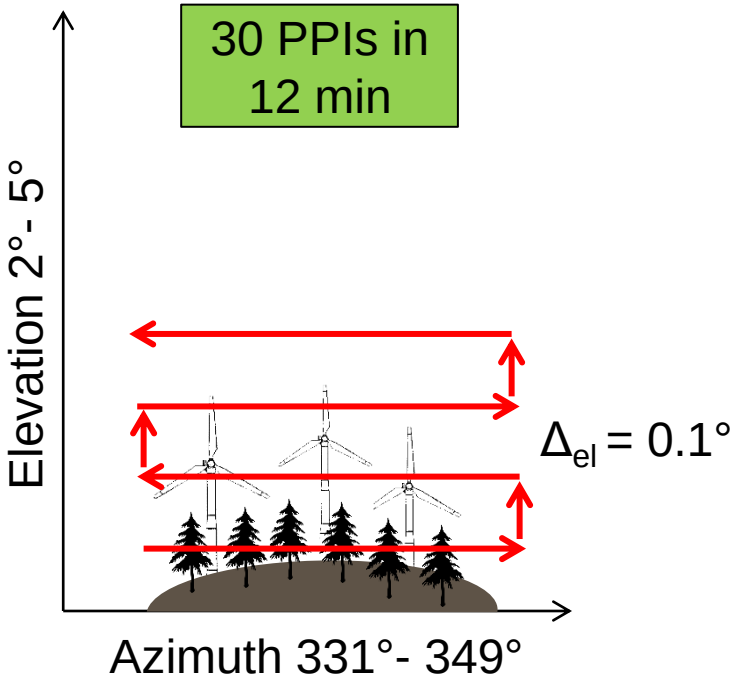


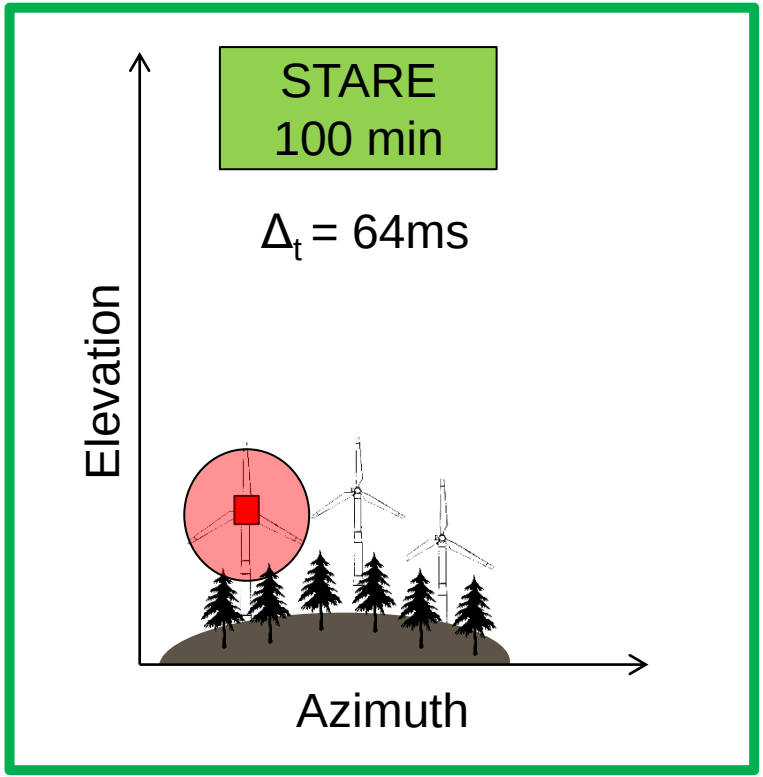


Maximum and median Z_H in 2019

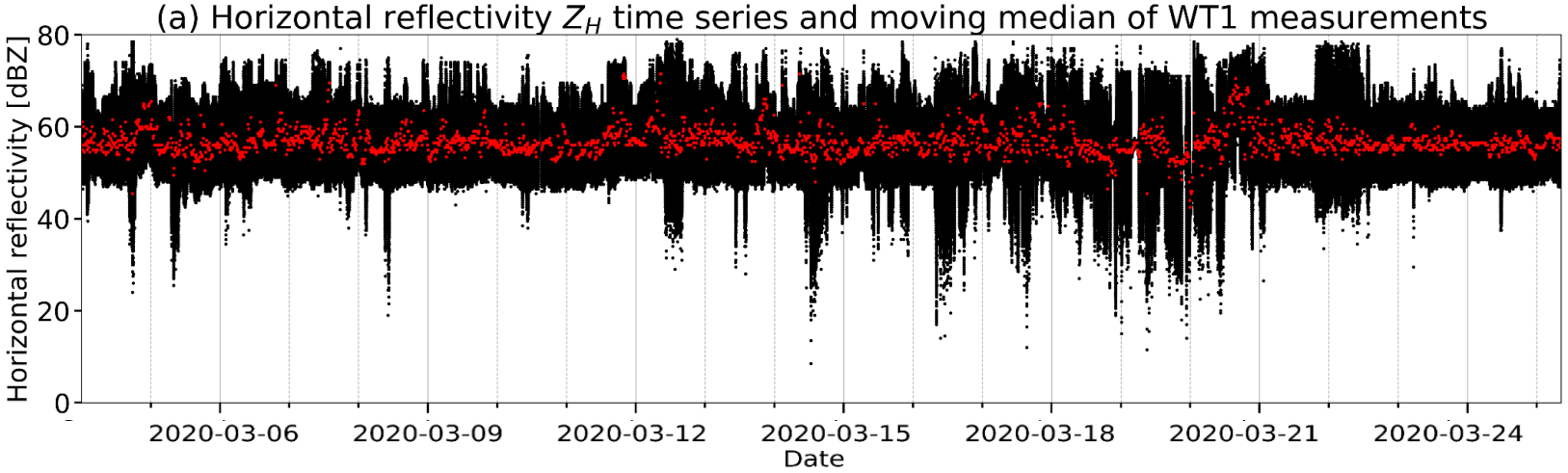


Scanning strategy (2020)



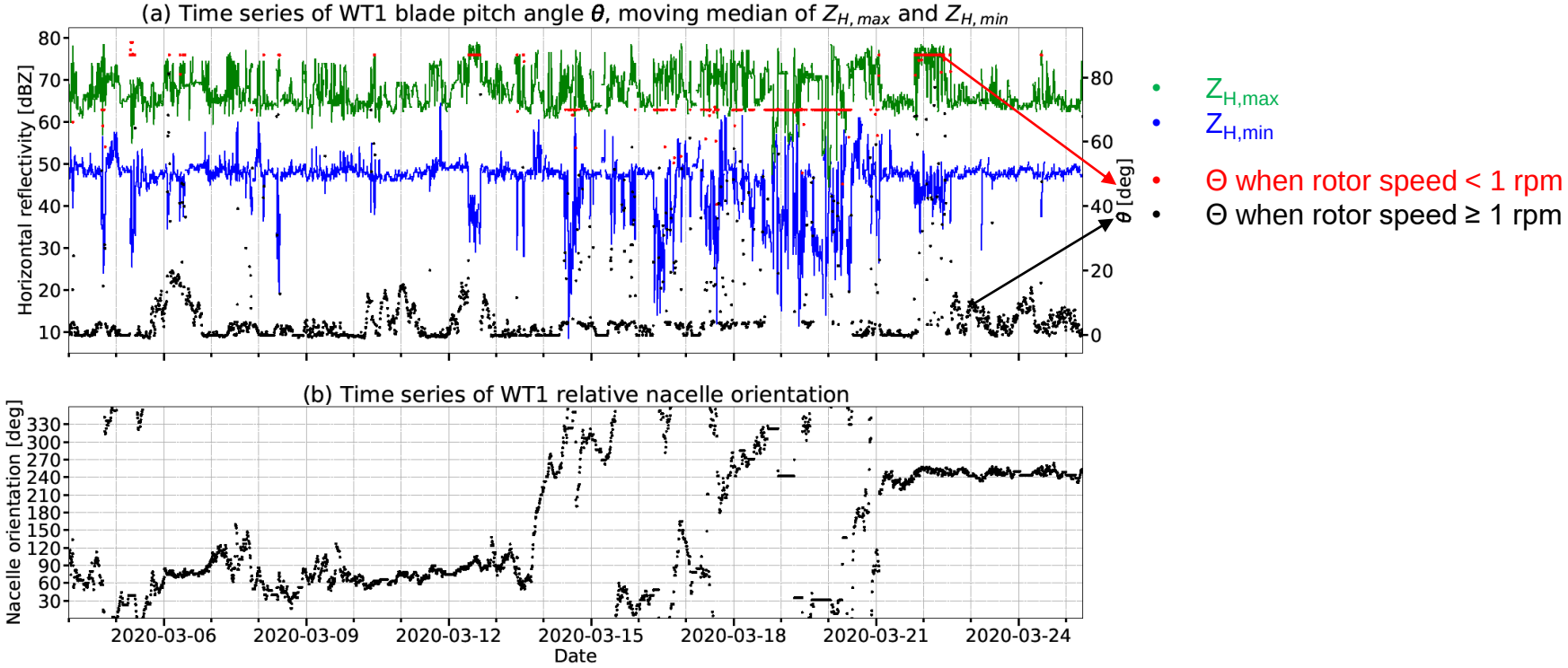


How data look like in 2020

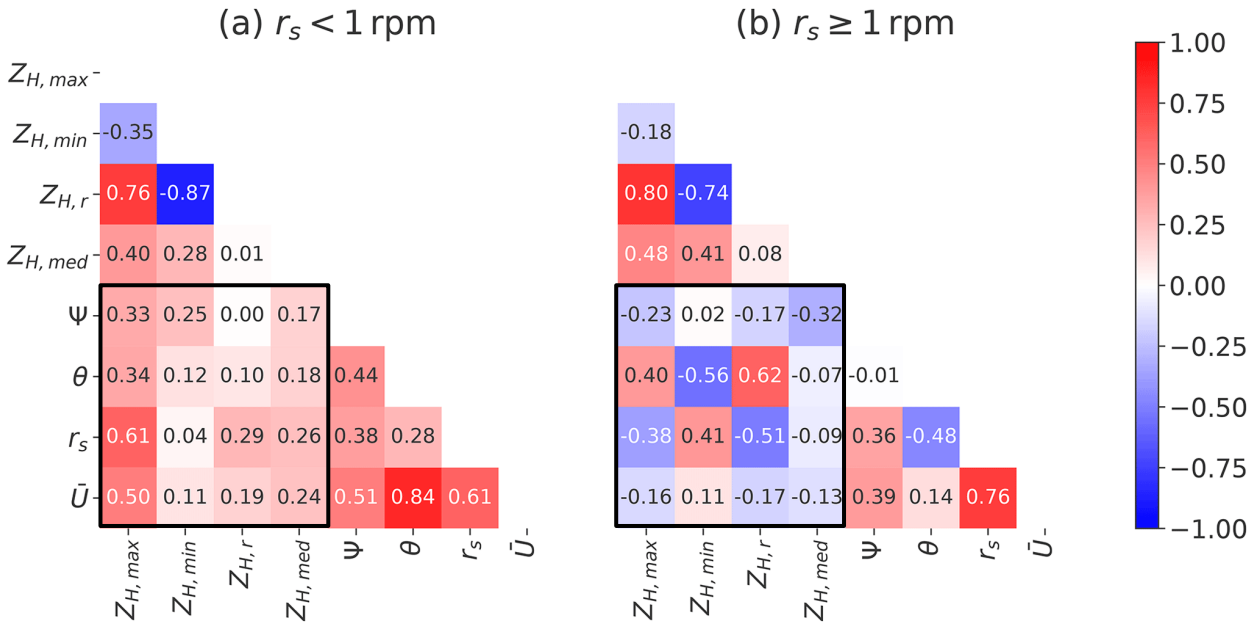


- Raw data in **black**, 10 min moving median in **red**
- High variability, with typical short-term spans of about 20dB
- Max Z_H reaches 78.5 dBZ (equivalent RCS: 44.1 dBsm)

Time series overview of 10 min data 2020

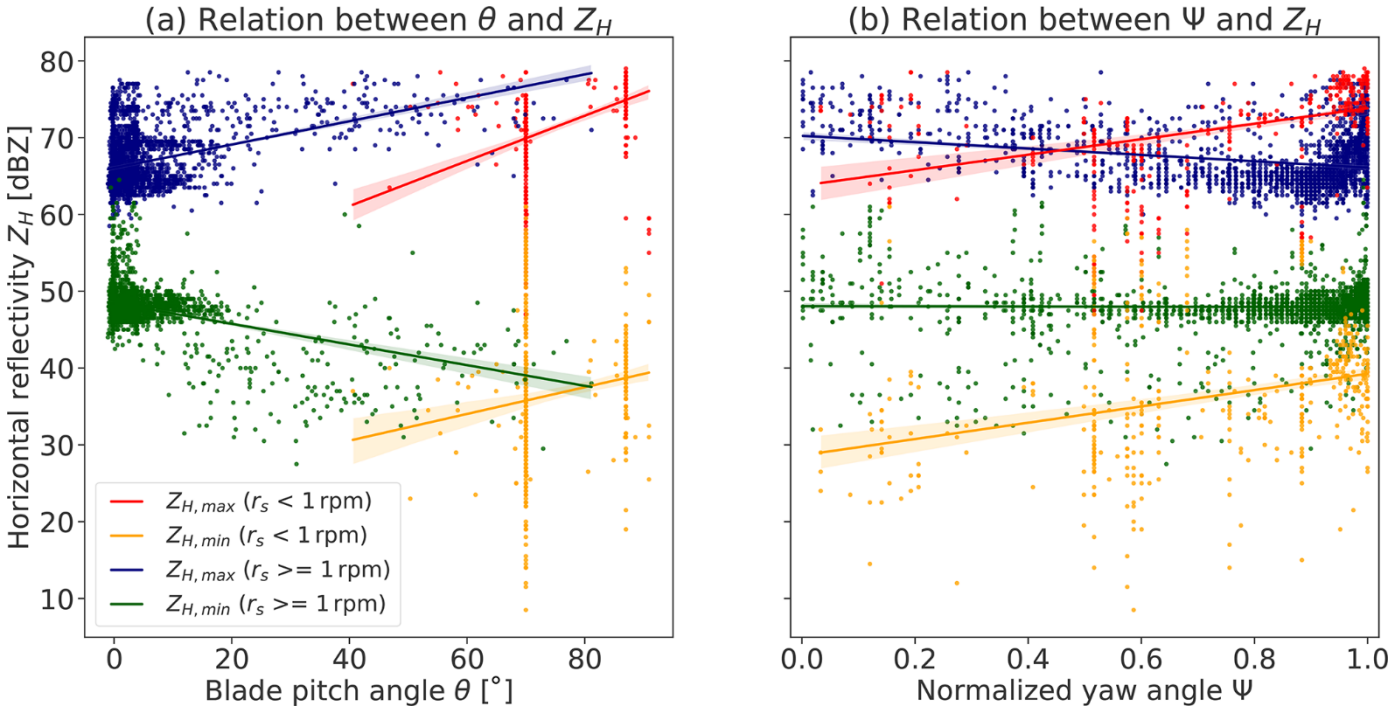


Correlation coefficient heat map



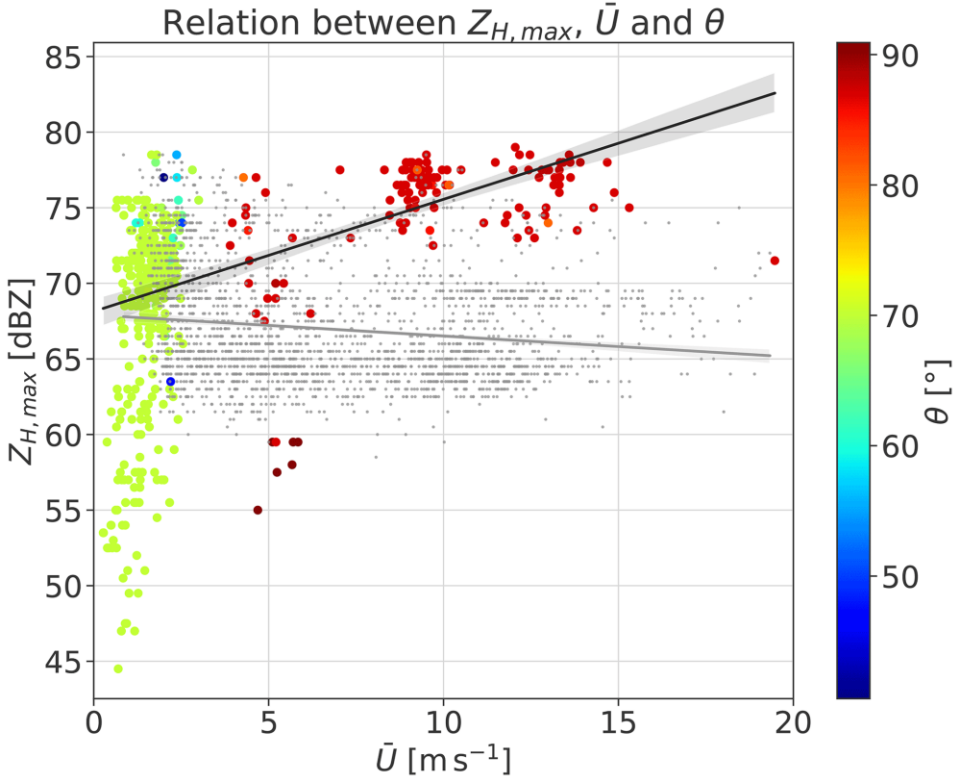
Ψ = |sin(α)|, Ψ ∈ [0,1]
α: rel. nacelle orientation
Θ: blade angle
Ū: mean wind speed

Relation between Z_H and {Θ,Ψ}



Ψ = |sin(α)|, Ψ ∈ [0,1]
α: rel. nacelle orientation
Θ: blade angle

Relation between $Z_{H,max}$ and {$\bar{U}$,Θ}

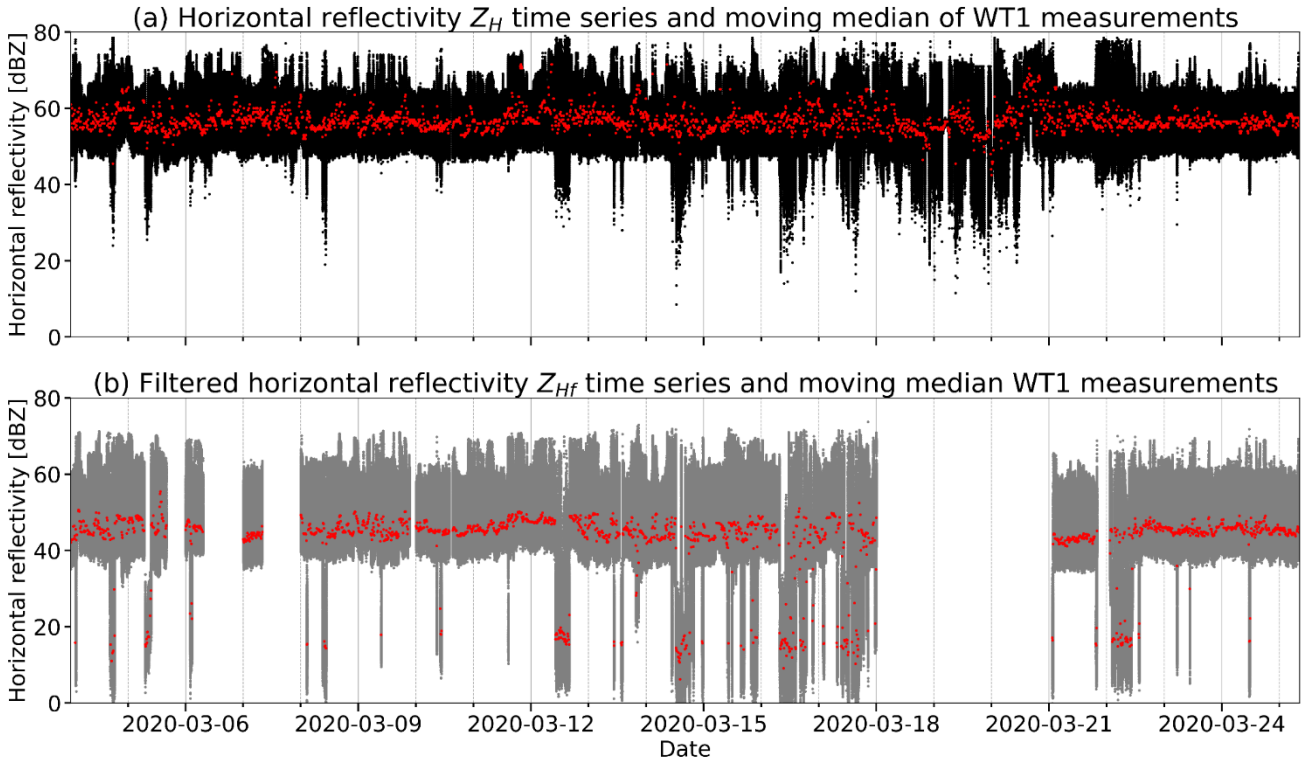


Θ: blade angle
$\bar{U}$: mean wind speed
r_s < 1 rpm (colored points)

Conclusions

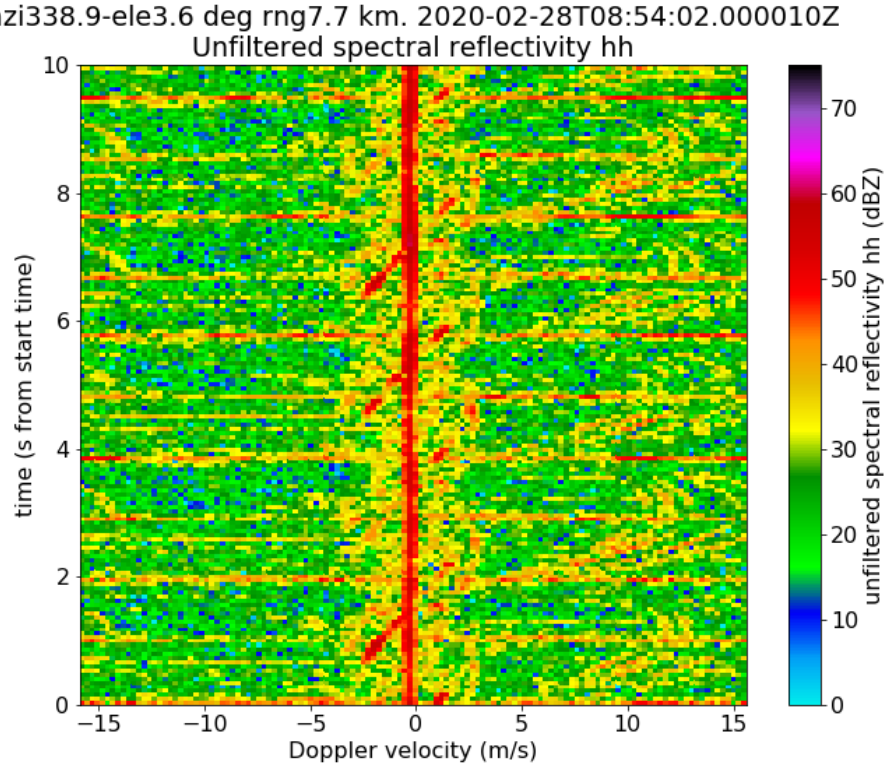
- Unique dataset of wind turbine observations at X-band
  - 2019: scanning (RHI/PPI volumes)
  - 2020: fixed antenna
- **Maximum RCS** ~40 dBsm (2019), ~44 dBsm (2020)
- **Large variability** of returns found in time-series analyses
  - $Z_{H,max}$ increases as the blade pitch angle θ increases, and this is especially true when the rotor speed is slow (sailing or aero-breaking mode)
  - Positive correlation of $Z_{H,max}$ and negative correlation of $Z_{H,min}$ for normal (power production) WT operation mode ($r_s \geq 1$ rpm)
  - For high wind speeds accompanied by aero-breaking pitch angles, the $Z_{H,max}$ variability is reduced. A moderate positive correlation ($Z_{H,max}$ vs. $\bar{U}$) for r_s below 1 rpm (effect of aero-elastic blade bending ?)

Unfiltered versus filtered Z_H 2020



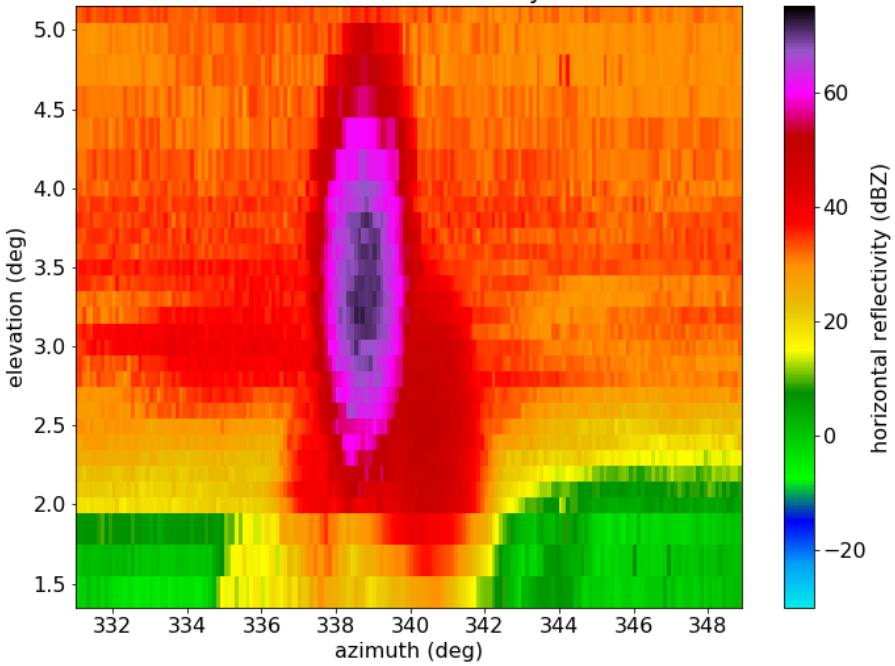
Clutter notch Doppler-filter of 7 m/s applied

A closer look to temporal variation

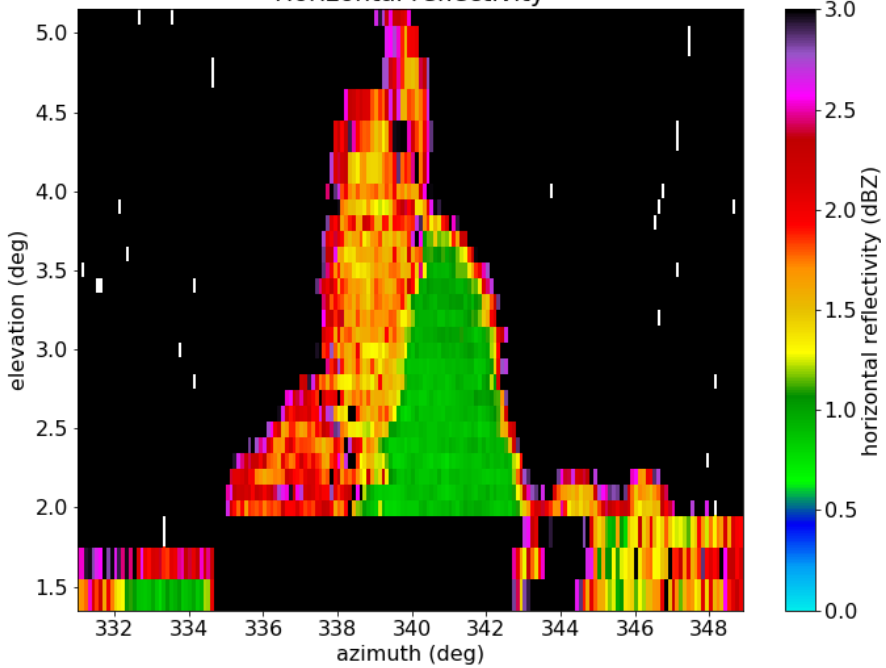


Statistics MAX and COV for WT1 (2019)

MAX



COV



Radar Cross Section retrieval

- Used to generalize the collected measurements:

$$P_R = 10 \cdot \log_{10} \frac{P_t \, G^2 \lambda^2 \sigma_B}{(4\pi)^3 r^4}$$

RCS

$$Z_H = P_R + \ C_H + 20 \cdot \log_{10} r + \ r \ \cdot C_A + \ L_{mf}$$

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