



Towards Improved Wind Turbine Clutter Detection Using Real-Time Turbine Operational Data

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Abstract. Weather radar is essential for precipitation monitoring, nowcasting and severe-weather warning. However the increasing deployment of wind turbines near radar sites increasingly compromises operational data quality. Rotating turbine blades enhance Doppler spectral noise floor, which can be used for automated clutter detection, but the detectability of wind turbine clutter (WTC) depends on turbine operation and radar-turbine viewing geometry. This study investigates the drivers of WTC detection using one year operational radar observations and two months spotlight-mode scans of an individual turbine from the German Meteorological Service (DWD, Deutscher Wetterdienst) weather radar at Boostedt, together with operating data from twelve turbines at Gönnebek at 30 s resolution. The available turbine operating data correlate well with the observed WTC at a temporal resolution of 5 min. This sampling interval is sufficient to capture the relevant temporal variability of WT operation data, whereas aggregation to 10 min or longer increasingly reduces temporal information. The detection algorithm is largely insensitive to precipitation compared to clear sky condition. Rotor speed is the dominant control on detectability while radar-relative nacelle orientation provides an additional, site-dependent contribution. Front- and back-view geometries yield broader Doppler signatures and more reliable detection, whereas side-view echoes often occur as short-lived spectral flashes that routine scans and therefore the WTC detection algorithm may miss. Blade pitch angle has little independent explanatory power once rotor speed is considered. Future assessments should account for turbine operation and radar-beam geometry in addition to distance from the radar. Extending detection to turbine-affected dual-polarimetric variables is needed because their impact may extend beyond the area identified by the current WTC-Flag.

1 Introduction

Weather radar observations are a key component of operational meteorology, providing spatially continuous information for precipitation monitoring, nowcasting, severe-weather warnings, hydrological applications, and numerical weather prediction (Fabry, 2015). The German C-band polarimetric weather radar network operated by the German Meteorological Service (DWD) is required to provide high-quality radar measurements with well-characterized uncertainties and stable long-term performance. The global expansion of renewable energy over the past few decades has led to a massive increase in the number of wind turbines. While this development is a central pillar of the energy transition, it poses significant challenges for meteorological remote sensing (e.g. Lainer et al., 2021; Frech et al., 2026). Wind Turbine Clutter (WTC) severely compromises the



25 quality of weather radar data, as the rotating blades generate broad Doppler spectra that frequently overlap with meteorological
signals (Isom et al., 2009). This leads to biases in precipitation estimation (QPE), false alarms in severe weather warnings
(see e.g. Seltnann and Böhme, 2017), and a general decrease in radar sensitivity (e.g. Frech et al., 2026; Isom et al., 2009).
Following the recommendations of the World Meteorological Organization, wind turbine installations close to weather radars
require careful assessment in the 20 km range of the radar, since they may cause both clutter contamination and partial beam
30 blockage (World Meteorological Organization (WMO), 2010). These two effects compromise radar data quality in different
ways as clutter contamination introduces non-meteorological echoes and Doppler-spectral distortions, whereas beam blockage
reduces the power returned from meteorological targets located behind the turbines. In Germany, wind turbines may now be
built within the formerly restricted 5-15 km range around weather radar sites, increasing the need for objective monitoring and
quantitative assessment of their impact on radar data quality. Subsequently, methods to mitigate the WTC clutter are urgently
35 needed.

DWD has implemented a dynamic detection algorithm directly within the signal processor. This algorithm utilizes the physical
property of rotating turbines to generate broadband noise in the Doppler spectrum, which is recorded as non-coherent power
(NCP) (Gerhards and Tracksdorf, 2021). In combination with a clutter ratio (CR) threshold, static targets can be distinguished
40 from the dynamic wind turbine signatures (Gerhards and Tracksdorf, 2021). Frech et al. (2026) evaluated the algorithm and
showed that the dynamic WTC detection algorithm performs well when wind turbines are operating, although missed detec-
tions may occur when the static clutter contribution from the turbine tower remains dominant. Their study identifies rotor speed
as a dominant predictor of WTC detection. While previous studies emphasized the importance of pitch angle and nacelle ori-
entation (yaw angle), further research is still needed (Lainer et al., 2021; Gabella et al., 2023). The dependence of operational
45 WTC detectability on turbine operating parameters and radar-turbine viewing geometry remains insufficiently characterized. In
particular, rotor speed, nacelle orientation, blade pitch angle, turbine state, and atmospheric conditions may influence whether
a wind turbine produces a detectable clutter signature in an operational radar scan. Real-time turbine operator data provide a
unique opportunity to relate radar-based WTC detections directly to the physical and operational state of the wind turbines.
Assessing the consistency and representativeness of these data within and across a wind farms is a prerequisite for their poten-
50 tial future use in operational WTC detection, mitigation, and radar-filtering applications.

In this study, we use high-resolution turbine operator data at 30 s resolution from the Gönnebek wind farm near the DWD
Boostedt radar together with operational C-band radar measurements to quantify the main drivers of WTC detectability. Such
data also make it possible to separate turbine-operating effects from site-specific radar-viewing effects and to assess which
55 predictors are transferable between different wind farms. Dedicated spotlight-mode scans are used to show that missed detec-
tions in side-view geometries are not necessarily caused by weaker turbine echoes, but can result from short-lived, intermittent
Doppler-spectral signatures that are not reliably sampled by the operational volume scan.



2 Wind turbine clutter detection

2.1 Operational WTC detection algorithm

The WTC detection examined in this study is the operational algorithm implemented in the signal processor of the C-band weather radar network of the DWD. A detailed description of the algorithm and its operational implementation is provided in Frech et al. (2026) and Gerhards and Tracksdorf (2021). The algorithm exploits the characteristic Doppler spectral signature of rotating wind turbine blades. Rotor motion introduces broadband Doppler components that increase the spectral noise floor. This effect is quantified using the NCP derived from the Doppler spectrum following the approach of Wilfong et al. (2014). To distinguish wind turbine echoes from strong stationary clutter targets, the algorithm additionally evaluates CR, defined as the ratio between the spectral power at zero Doppler velocity and the estimated Doppler noise level. While stationary clutter produces a pronounced peak at zero Doppler velocity, wind turbine echoes are characterized by an elevated spectral noise floor and a less dominant zero-velocity peak. Potential WTC signatures are identified by a peak search in the NCP field along each radar ray using the high range sampling resolution of the radar measurements. Candidate peaks are then classified using threshold values of NCP and CR in order to separate wind turbine clutter from strong static clutter targets. Detected peaks are subsequently expanded to neighboring range bins and stored as dynamic WTC detections for further monitoring and processing. (Frech et al., 2026)

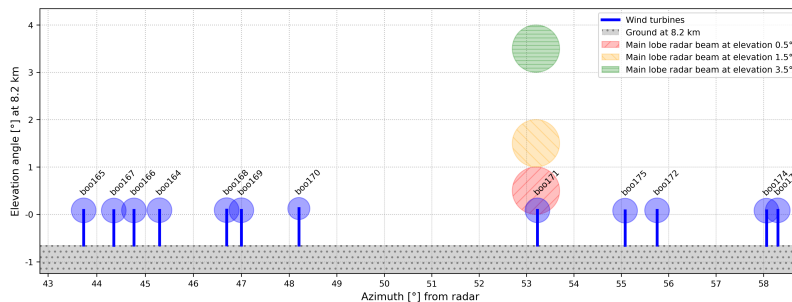


Figure 1. Schematic illustration of the Boostedt radar 3 dB main lobe at elevation 0.5° (red), 3 dB main lobe at elevation 1.5° (orange) and 3 dB main lobe at elevation 3.5° (green) intersecting the Gönnebek wind farm (turbines in blue). The inset focuses on turbine b00171 at an azimuth of 53.2° and shows the cross-section of the rotor-blade plane where it is intersected by the radar beam at elevation 0.5°.

2.2 Study site and data sets

The study site examined in this work is the wind farm Gönnebek, located in northern Germany 7.3 km to 8.4 km northeast of the C-band weather Boostedt radar. A PPI plot of uncorrected reflectivity (horizontal channel) (Th) and uncorrected depolarization ratio (UDR) from the Boostedt radar, with the Gönnebek wind turbines overlaid in black, is shown in Figure 2. The wind farm consists of 12 turbines with hub heights ranging from 104.7 m to 110 m and total heights between 176.6 m to 179.25 m. The wind farm covers an area of approximately 3 km². The turbines started operating between May 2025 and June

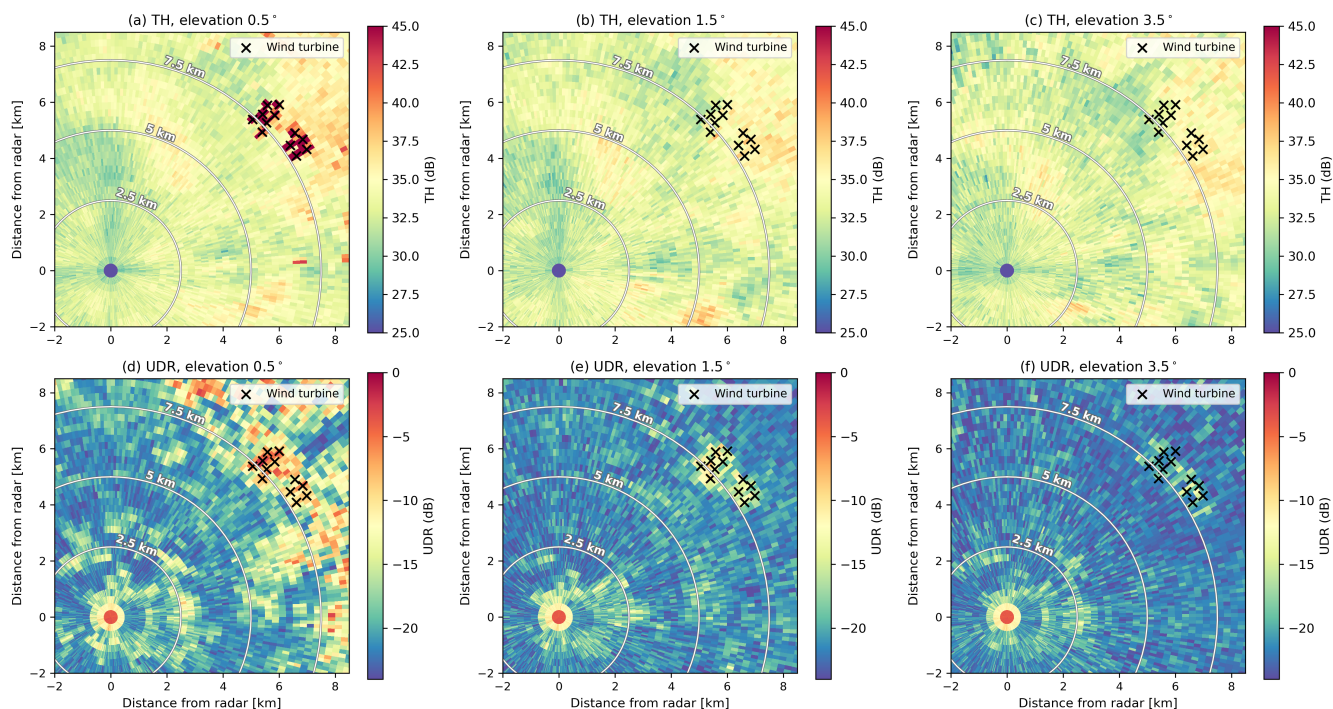


Figure 2. Uncorrected radar reflectivity (TH; a-c) and uncorrected differential reflectivity (UDR; d-f) around the Boostedt radar. Wind turbines of the Gönnebek wind farm are marked in black. Panels (a) and (d), (b) and (e), and (c) and (f) show data at antenna elevations of 0.5° , 1.5° , and 3.5° , respectively. The observations were acquired during a stratiform precipitation event on 4 October 2025.

2025. Operational data from the turbines are delivered in real time at 30 s intervals. The data set includes nacelle orientation
80 (yaw angle), rotor blade pitch angle, rotor speed, temperature and pressure at nacelle level, wind speed and wind direction at nacelle level, turbine state (online, offline, startup, shutdown, brake), and timestamps of operational stops. For comparison, turbine operational data and corresponding radar observations from the Laichingen wind farm (Frech et al., 2026), are used to assess the transferability of the viewing-geometry dependence identified at Gönnebek.

85 Radar data from Boostedt are used to extract the WTC detections signals at elevations of 0.5° and 1.5° . At 0.5° elevation, the radar beam intersects more than half of the turbine rotor area, producing strong radar signatures and high detectability of WTC. A schematic of the radar–turbine geometry is shown in Figure 1. In contrast, only very few WTC detections flags are detected at 1.5° , consistent with the findings of Frech et al. (2026). However, this does not imply the absence of turbine-induced radar signatures at higher elevations. Although the signal strength decreases with elevation, wind turbine effects were detected up to
90 3.5° within a radius of 5 km and up to 1.5° at distances between 5 km to 15 km by Frech et al. (2026). These effects are particularly evident in dual-polarimetric variables, as shown in Figure 2. The affected radar volume is larger than that associated with single-polarization moments, confirming the findings of Frech et al. (2026). The current detection scheme, however, is not



parameterized to detect the wind turbine impact zone on polarimetric moments. Extending the detection approach accordingly is therefore important for a more complete characterization of turbine-induced disturbances and for improving the quality control and usability of operational radar data.

For each turbine, WTC-Flag along with radar moments CR, NCP, clutter correction (CCor), Th, uncorrected reflectivity (vertical channel) (Tv), uncorrected cross correlation coefficient (URHOHV) and UDR are analyzed. Radar parameters are extracted from a 3×3 range bin area surrounding each turbine, excluding the turbine’s own range bin, and are subsequently averaged to account for beam broadening effects. The combination of high-resolution operational data and radar observations enables detailed validation of the WTC detection algorithm, including rotor-speed dependence, operational state correlation, and directional effects. The analyses are based on a combination of turbine operational data, operational radar measurements, WTC monitoring output, spotlight-mode scans, and post-processed beam-blockage products. An overview of these data sets is provided in Table 1.

Table 1. Overview of the main data sets used in this study.

Data set	Source	Period	Resolution / sampling	Main content	Use
Gönnbek turbine data	Wind-farm operator	Sep 2025–Aug 2026	30 s	Operational data from 12 turbines: rotor speed, pitch angle, nacelle orientation, wind speed and direction at nacelle height, turbine state, temperature, pressure and stop events.	Validation of WTC detectability and turbine-parameter dependence.
Laichingen turbine data	Wind-farm operator	Sep 2025–Aug 2026	10 min	Operational data from 2 turbines: rotor speed, nacelle orientation, wind speed and direction at nacelle height, turbine state, temperature and stop events.	Comparison data set for evaluating the transferability.
WTC database	DWD Boostedt radar and Türkheim	Sep 2025 – Aug 2026	5 min	Operational radar moments and WTC-Flags from the volume scan, including Th, CR, NCP, CCor, URHOHV, and UDR.	Detection analysis, and weather/clear-sky classification.
spotlight-mode scans	DWD Boostedt radar	Jun 2026 – Jul 2026	20 min scan interval; ~10 s dwell time	Dedicated scans toward turbine bo0171, including radar moments and Doppler spectra.	Analysis of spectral signatures and viewing-geometry effects.

2.3 Validation using turbine operational data

2.4 Temporal harmonization and consistency of turbine operational data

This section examines how the available operator data can be used to improve the interpretation of WTC detections and to identify their strengths and limitations. We determine the temporal resolution required for a robust comparison with radar observations. The validation covers September 2025 to August 2026. Radar observations from the Boostedt radar follow the DWD operational 5 min scan strategy introduced in 2012, consisting of a horizon-following precipitation scan, a 10-elevation volume

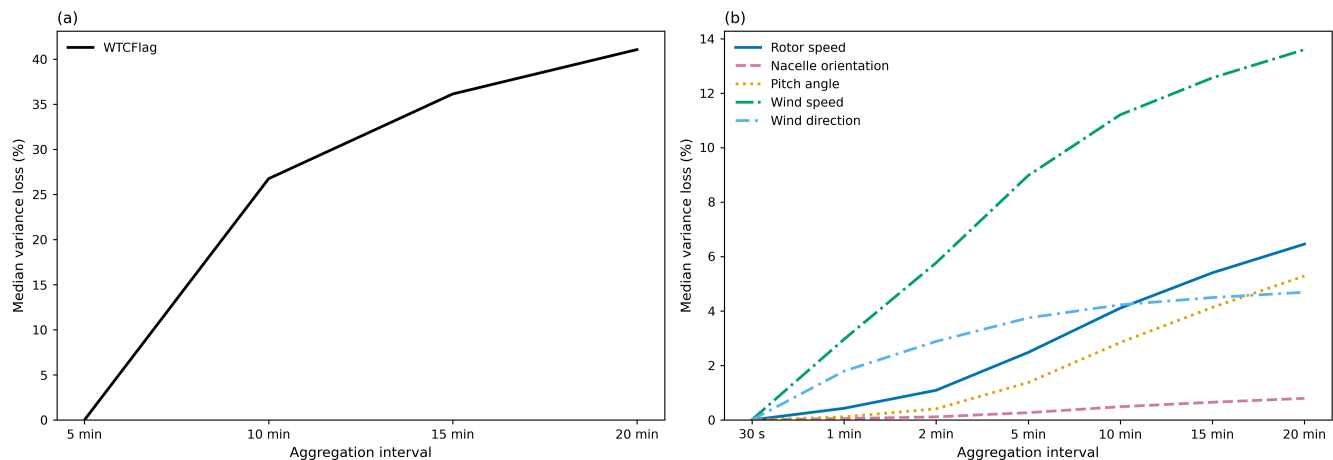


Figure 3. Impact of temporal aggregation of WTC-Flag and turbine operational data. Variance loss is computed as the within-bin sum of squares relative to the total sum of squares of the corresponding reference time series, i.e. the fraction of variability removed when samples within an aggregation bin are replaced by their bin mean. The left panel shows the binary WTC-Flag relative to an operational 5 min radar time base, constructed using maximum aggregation, for intervals from 5 to 20 min. The right panel shows turbine operating parameters relative to the native turbine time series for intervals from 30 s to 20 min. Nacelle orientation and wind direction are treated as circular variables using sine and cosine components. Curves indicate the median across turbines.

scan and a 90° birdbath scan (Seltmann et al., 2013). While the individual radar measurements are acquired at high temporal resolution, the operational volume products have an effective temporal resolution of about 5 min. Turbine operational data are available at a nominal 30 s reporting interval. To synchronize both datasets, radar timestamps are rounded to the nearest 5 min and matched to the closest turbine observation within maximum ± 1 min using an as-of merge, yielding identical numbers of radar and turbine observations per turbine. After matching, the radar timestamp was retained as the primary timestamp for all subsequent analyses. In total, 927,344 turbine observations from all 12 turbines were analysed.

Typical WTC events persist over multiple radar scans. Across the 12 turbines in Gönnebek 97,188 WTC episodes were identified. The median observed episode duration is 10 min and the mean duration is approximately 30 min, while the 90th percentile is 65 min. Only the longest 10% of episodes exceed about one hour, and only the longest 1% exceed approximately 5 h. Rare extremes can persist for up to about 8 h to 2 days within the one year observation period analyzed here. These statistics show that most WTC episodes extend over more than one operational radar volume scan. However, the variance-loss analysis, defined as the within-bin sum of squares relative to the total sum of squares of the 5 min reference WTC-Flag time series, indicates that preserving the 5 min radar time scale is important for retaining the temporal structure of the binary WTC-Flag see Figure 3. Aggregating the WTC-Flag from the 5 min radar basis to 10, 15, and 20 min removes a median fraction of variance of approximately 25 %, 33 %, and 38 %, respectively. The corresponding median hard-decision mismatch rates, calculated as the fraction of 5 min reference time steps for which the binary reference flag differed from the binwise aggregated flag (set to



one when the within-bin event fraction was ≥ 0.5), were 10.6 %, 10.7 %, and 12.7 %, respectively. Thus, at a 10 min resolution, the assigned WTC status differs from the 5 min reference in approximately 10 % of cases, exclusively through false-positive assignments when only one of the two constituent 5 min intervals is flagged. While coarser wind turbine operation data may still capture the occurrence of many longer events, it increasingly degrades their timing and intermittency and thus the false acceptance rate in WTC detection increases.

To assess the temporal resolution required for turbine operational data, we compared multiple aggregation levels from 30 s to 20 min (30 s, 1 min, 2 min, 5 min, 10 min, 15 min, and 20 min; see Figure 3). For each turbine parameter, the effect of temporal aggregation was quantified by the variance loss, defined as the within-bin sum of squares relative to the total sum of squares of the corresponding reference time series. It therefore represents the fraction of variability removed when samples within an aggregation bin are replaced by their bin mean. For turbine operating parameters, the native turbine time series was used as the reference, whereas for the binary WTC-Flag the reference series was first constructed on the operational 5 min radar time base. Variance loss was computed separately for each turbine and then summarized across turbines using the median, yielding the reported median variance loss for each parameter and aggregation interval.

For the turbine parameters 8,196,784 turbine observations from all 12 turbines were analysed. 8,196,784 turbine observations from all 12 turbines were analysed. Variance loss remained small within 2 min aggregation and moderate at 5 min aggregation, with median values of 0.3 % for nacelle orientation, 1.1 % for pitch angle, 2.0 % for rotor speed, 3.9 % for wind direction, and 9.4 % for wind speed. Aggregation uncertainty was calculated as the median across turbines of the 95th-percentile absolute differences between native and temporally aggregated values, representing the range containing approximately 95% of direct aggregation deviations. The central 95 % intervals were $\pm 5.0^\circ$ for nacelle orientation, $\pm 1.1^\circ$ for pitch angle, ± 0.90 rpm for rotor speed, $\pm 19^\circ$ for wind direction, and $\pm 1.5 \text{ m s}^{-1}$ for wind speed. Coarser aggregation to 10-20 min led to progressively wider residual intervals and larger variance losses. At 10 min, the central 95 % intervals had widened to $\pm 6.7^\circ$ for nacelle orientation, $\pm 2.1^\circ$ for pitch angle, ± 1.2 rpm for rotor speed, $\pm 21^\circ$ for wind direction, and $\pm 1.7 \text{ m s}^{-1}$ for wind speed. These results indicate that the effective radar-turbine coupling relevant for the present implementation is mainly controlled by the radar sampling interval of about 5 min rather than by sub-minute turbine fluctuations. With aggregation intervals of 10 min or longer, relevant turbine-operational information is increasingly lost, as indicated by 95th-percentile absolute differences exceeding ± 1.0 rpm for rotor speed and $\pm 5.0^\circ$ for nacelle orientation. In contrast to process-oriented studies such as Gabella et al. (2023), which emphasize that 10 min turbine metadata are too coarse to resolve rapid turbine-state changes in detail, our results show that such rapid changes contribute only weakly to the variance of the turbine parameters considered here. In this context, the radar temporal resolution imposed by the DWD scan strategy of about 5 min represents the dominant temporal constraint. Accordingly, turbine metadata aggregated to the radar scan interval are sufficient to capture the dominant operational states relevant for the present WTC-Flag-based application, whereas coarser aggregation to 10 min and beyond increasingly removes relevant temporal information. Higher native turbine resolution is therefore expected to provide only limited additional benefit for this specific operational implementation, although it may still be valuable for process-oriented analyses or alternative de-



tection strategies based on high-rate turbine telemetry, for example to model and subtract state-dependent turbine signatures from stare-mode radar observations (e.g. Beauchamp and Chandrasekar, 2017).

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Assessing the spatial consistency of turbine operational data is essential to establish their reliability for attributing variations in radar-based wind turbine clutter detection to turbine operation and radar-viewing geometry. This evaluation is particularly important for the potential future use of operator data in WTC detection, mitigation or filtering applications. To assess the consistency of the turbine operational data across the wind farm, pairwise correlations between turbines were calculated for several key variables. Temperature and pressure measured at nacelle level show extremely high correlations (mean correlations of ≈ 0.95 and ≈ 0.92), indicating nearly identical large-scale atmospheric conditions across the wind farm, good data quality and a consistency of the measurement devices used. Nacelle orientation and wind direction are also highly correlated (≈ 0.86 and ≈ 0.76), confirming a spatially coherent wind direction field. In contrast, wind speed exhibits only moderate correlations (≈ 0.57). This reduced coherence may reflect both measurement uncertainties and genuine spatial variability of the wind field within the wind farm. The wind farm covers approximately 3 km^2 . Turbine wakes can affect downstream flow over several rotor diameters (e.g., Barthelmie and Jensen, 2010; Stevens and Meneveau, 2017; Vermeer et al., 2003) or even much further (Platis et al., 2020; Porté-Agel et al., 2020) and therefore reduce pairwise wind speed correlations. We calculated the mean pairwise Pearson correlation as a function of mean rotor speed across the wind farm, excluding turbine b00174 due to measurement inconsistencies. The correlation decreased from approximately 0.73 at 0-1 rpm to 0.29 at 9-10 rpm. This trend suggests increasing spatial decorrelation at higher rotor speeds, supporting the hypothesis that wake effects on the wind speed measurements contribute more strongly to the observed decorrelation. Operational control parameters such as rotor speed and pitch angle show lower correlations (≈ 0.58 and ≈ 0.58), reflecting turbine-specific control behavior rather than purely meteorological forcing. Overall, the coherence analysis confirms that the turbine measurements are physically consistent and dominated by a common large-scale wind forcing, while turbine control processes and local wind field variability introduce additional variability in measurements of wind speed, rotor speed and pitch angle.

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2.5 Rotor-speed dependence of WTC detectability

To characterize the detection behavior, the detection rate was analyzed as a function of rotor and wind speed (Figure 4). The detection rate increases strongly with rotor speed and corresponding wind speed, consistent with the behavior reported by Frech et al. (2026). Most turbine operation occurs between 5 rpm and 11 rpm, where the detection rate rises steadily. Maximum rates above 80% are reached at around 7 rpm, corresponding to wind speeds of approximately 9 m s^{-1} . The turbines show broadly consistent detection behaviour, suggesting that, within this wind farm, WTC detectability is largely insensitive to turbine-specific characteristics. The only notable exception is b00174, which exhibits a lower detection probability than the other turbines.

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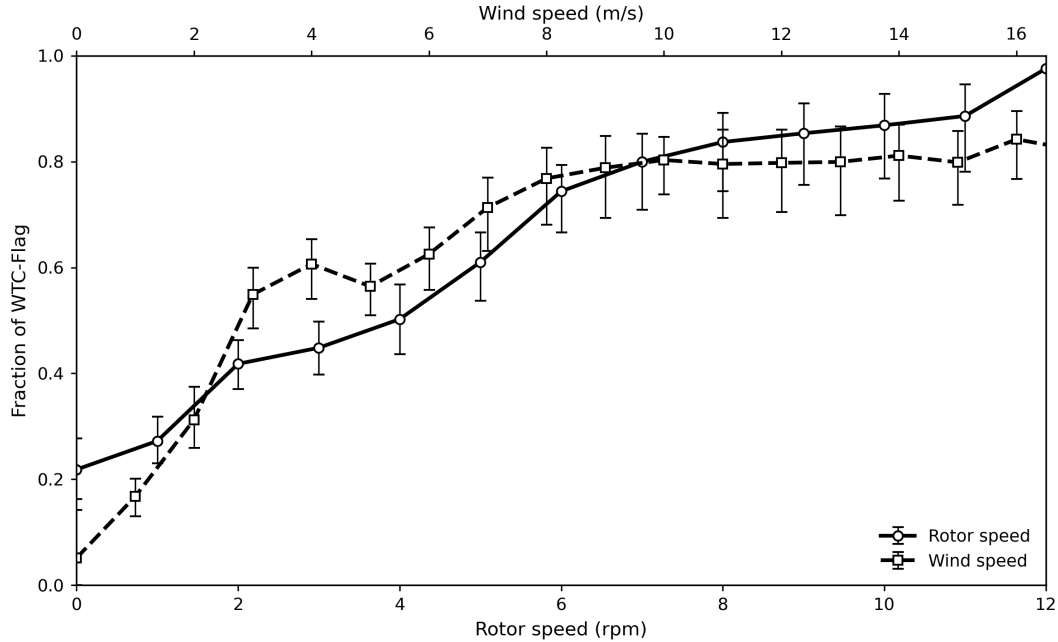


Figure 4. Mean WTC detection rate for all 12 turbines at an elevation of 0.5° . The fraction of WTC-Flags as a function of rotor speed is shown by the solid line, while the dashed line indicates the corresponding dependence on wind speed. Error bars indicate 95 % bootstrap confidence intervals of the mean detection rate across turbines for each rounded speed bin. 927,344 turbine observations were analysed.

2.6 Viewing-geometry dependence of WTC detectability

The following analysis extends the evaluation of Frech et al. (2026) by examining the directional dependence of WTC detection with respect to the nacelle orientation (yaw angle) relative to the radar. The yaw angle distribution across all turbines shows broad coverage from 0° to 360° , with most observations concentrated in bins between 60° and 270° ($\sim 70\%$ of data points). Figure 5 shows exemplary polar plots for turbine `b00171`, with nacelle orientation represented in azimuth and rotor speed in the radial direction. The depicted relationships are representative of the behaviour observed across the analysed wind turbines, except for `b00174`, which exhibits measurement inconsistencies, as discussed in subsection 2.3. The four panels show (a) the distribution of cases across nacelle-orientation–rotor-speed sectors, (b) the fraction of (DBZh)-invalid cases, (c) the fraction of valid cases with $WTC - Flag = 1$, and (d) the fraction of valid cases with $WTC - Flag = 0$. Panels (c) and (d) are jointly normalized within each sector and therefore sum to one, whereas panel (b) is normalized independently by the total number of cases in the respective sector. DBZh is classified as invalid if the quality-threshold criteria $CCor > -15$, > -8 , and $URHOHV > 0.25$ are not fulfilled. This occurs mainly for static clutter. The WTC-Flags are set independently of these DBZh validity criteria. DBZh invalid cases are distributed roughly equally on the classes WTC-Flag 0 and 1, while WTC flagged cases make up for 65% of all evaluated cases. The fraction of WTC-Flags varies strongly with yaw angle, ranging from a minimum of approximately 39% in the $330\text{--}360^\circ$ bin to a maximum of approximately 77% in the $210\text{--}240^\circ$ bin, demonstrating that radar

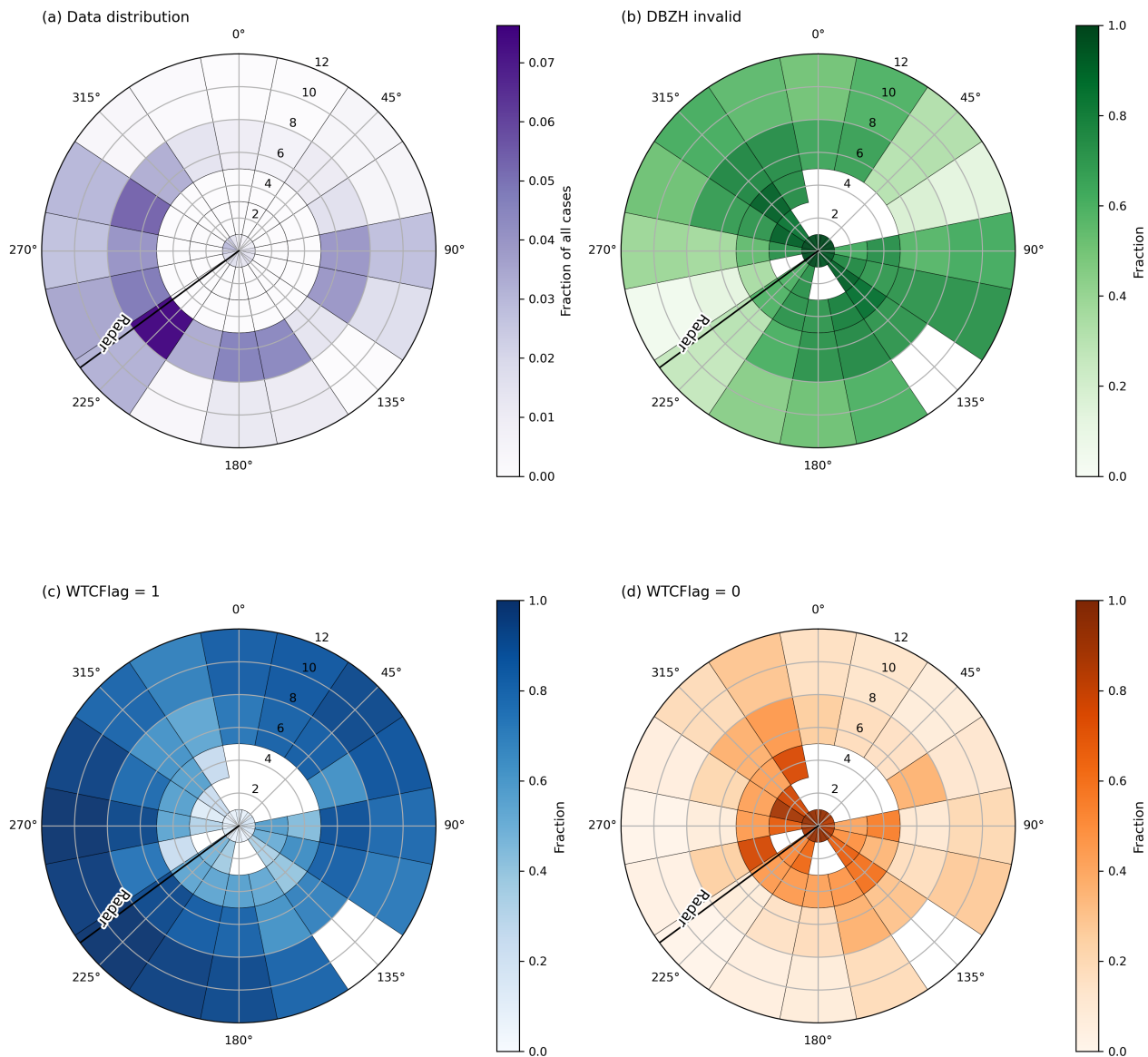


Figure 5. Polar plots showing the directional dependence of WTC detection for the wind turbine b00171 at an elevation of 0.5° . 77,849 cases were evaluated. The turbine is located at the center of the figure, the azimuth indicates the nacelle orientation relative to the radar, and the radial distance corresponds to the rotor speed. Each sector corresponds to one nacelle-direction-rotor-speed bin. The text “Radar” marks the radar line of sight. Panel (a) shows the relative data distribution, (b) shows the fraction of invalid DBZH values per bin. DBZH is considered invalid when the quality-threshold criteria $CCOR > -15$, $SNR > -8$, and $URHOHV > 0.25$ are not met, which mainly occurs for static clutter. The WTC-Flags are set independently of these DBZH validity criteria. Panels (c) and (d) show the bin-wise fractions of cases with WTC-Flag = 1 and WTC-Flag = 0, respectively. The two WTC-Flag fractions are normalized jointly within each bin and therefore sum to one where valid WTC-Flag data are available.

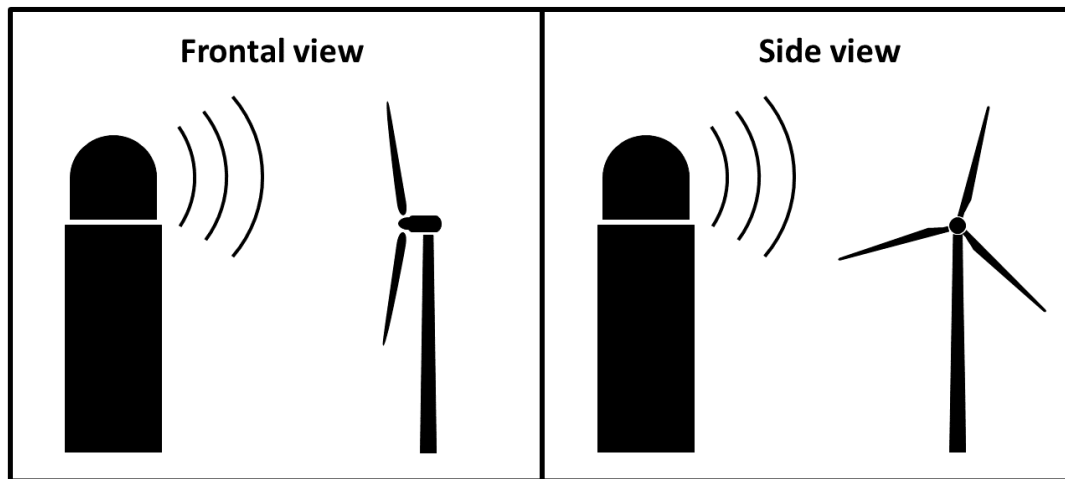


Figure 6. Front and side views of the radar–turbine geometry. The left panel shows the frontal view and the right panel the side view. In both cases, the radar is located to the left and observes the turbine on the right. The back view is analogous to the frontal view, except that the turbine is oriented away from the radar.

viewing geometry strongly affects detectability. The signal processor evaluates several threshold criteria for data quality control and for removing invalid range bins. When the nacelle orientation is approximately orthogonal to the radar line of sight and the rotor blades are aligned with the radar beam (see side view in Figure 6), a minimum in WTC-Flags coincides with a maximum in thresholded data. This suggests that these echoes are identified as non-valid by the currently implemented pre-processing methods and resemble the signature of stationary clutter. The highest detection rates occur when the nacelle faces toward or away from the radar (see frontal view in Figure 6), corresponding to rotor blades that are roughly perpendicular to the radar line of sight. However, the nominal nacelle-to-radar geometry provides only a simplified description of the actual scattering geometry. Beam broadening and the three-dimensional blade geometry, including blade pitch angle and tilt angle, imply that radial velocity components can arise even in nominally unfavourable viewing configurations. The tilt angle, i.e. the inclination of the rotor axis relative to the horizontal (see Appendix B Figure B1; Santo et al., 2020), further modifies the orientation of the rotor plane with respect to the radar beam and thereby influences the resulting radial velocity components. Thus, wind-turbine-affected Doppler spectral signatures may be present without necessarily triggering the operational WTC-Flag, motivating a more detailed analysis of the associated radar moments and Doppler spectra in order to improve the detection algorithm.

A comparison data set from turbine `tur3` at the Laichingen wind farm was used to examine the transferability of the results obtained for Gönnebek. The dependence of WTC detectability on rotor speed had already been investigated by Frech et al. (2026), who likewise found higher detection probabilities at higher rotor speeds. For high-rotor-speed cases between 8 and



12 rpm detection probability is highest when the nacelle is oriented approximately towards the radar and decreases towards side-view and rear-facing geometries (see Appendix B Figure B2). The front-to-side decrease is consistent with the behaviour observed at Gönnebek and thus provides initial evidence that the principal viewing-geometry dependence of WTC detectability may also occur at other wind farms. In contrast to Gönnebek, the detection probability at Laichingen does not show a similarly symmetric increase for rear-facing orientations. The DBZh-related quality information indicates that DBZh is thresholded in a large fraction of these cases, consistent with a substantial contribution from static clutter. Static turbine components, potentially including the nacelle and other structural elements that are more exposed for particular viewing directions, may contribute to the lower detection probability in the rear-facing sector in Laichingen. In addition, the radar beam intersects the turbine at a considerably lower height at Laichingen than at Gönnebek (Frech et al., 2026). Differences in turbine model and geometry, local surroundings, and radar measurement geometry may further influence the observed behaviour.

2.6.1 Radar-moment signatures in the operational radar data

To investigate which radar and turbine parameters are associated with the directional dependence of the operational WTC detection, we first analysed the radar moments stored in the WTC database itself. These moments are written during the operational volume scan every 5 min and contain the WTC-Flag together with radar moments from the wind-turbine pixel and co-located turbine operating parameters. The analysis was restricted to the two main viewing geometries (see Figure 6), front/back ($\alpha \geq 20^\circ$, nacelle facing towards/away from the radar) and side view ($\alpha \geq 70^\circ$, nacelle approximately orthogonal to the beam) and was limited to high-rotor-speed cases (rotor speed > 5 rpm). In front/back view, detected cases were associated with substantially higher rotor speeds than non-detected cases, with mean values of 8.2rpm and 6.9rpm, respectively. In side view, by contrast, the corresponding means were closer together, 7.2rpm and 6.7rpm, indicating that rotor speed is less discriminative for WTC detection in this geometry. The radar moments distinguish $WTC - Flag = 1$ from $WTC - Flag = 0$ in both geometries, albeit with different signatures and effect strengths (Figure 7). Th shows similar values for the front / back and side view with detected WTC. Side view cases without detected WTC have increased Th by 3.4dB. A clear geometry-dependent separation is found for clutter ratio (horizontal channel) (CRh) and non-coherent power (horizontal channel) (NCPh), both of which are directly relevant for the detection algorithm. In front/back view, CRh decreases strongly from a mean of 40 for non-detected cases to 23 for detected cases, whereas the decrease in side view is smaller, from 40 to 31. Since high CRh is indicative of strong quasi-stationary clutter, the higher CRh values retained in side-view detections suggest that side-view WTC signatures taken from the volume scan can be more similar to ordinary fixed clutter, which may make them more difficult to identify robustly. Consistently, NCPh increases much more strongly in front/back view, from 55 to 68, than in side view, from 59 to 65, indicating a clearer WTC-related signal enhancement in the front/back geometry. Signal Noise Ratio (horizontal channel) (SNRh) shows similar values for both viewing geometries with a larger variation being observed for the front / back view. Further differences are evident in the polarimetric variables. Clutter Phase Alignment (CPAh) quantifies the phase coherence of the Doppler spectrum. The metric is derived from the horizontally and vertically polarised radar channels and therefore reflects polarisation-dependent differences in echo coherence. CPAh is systematically higher in side view

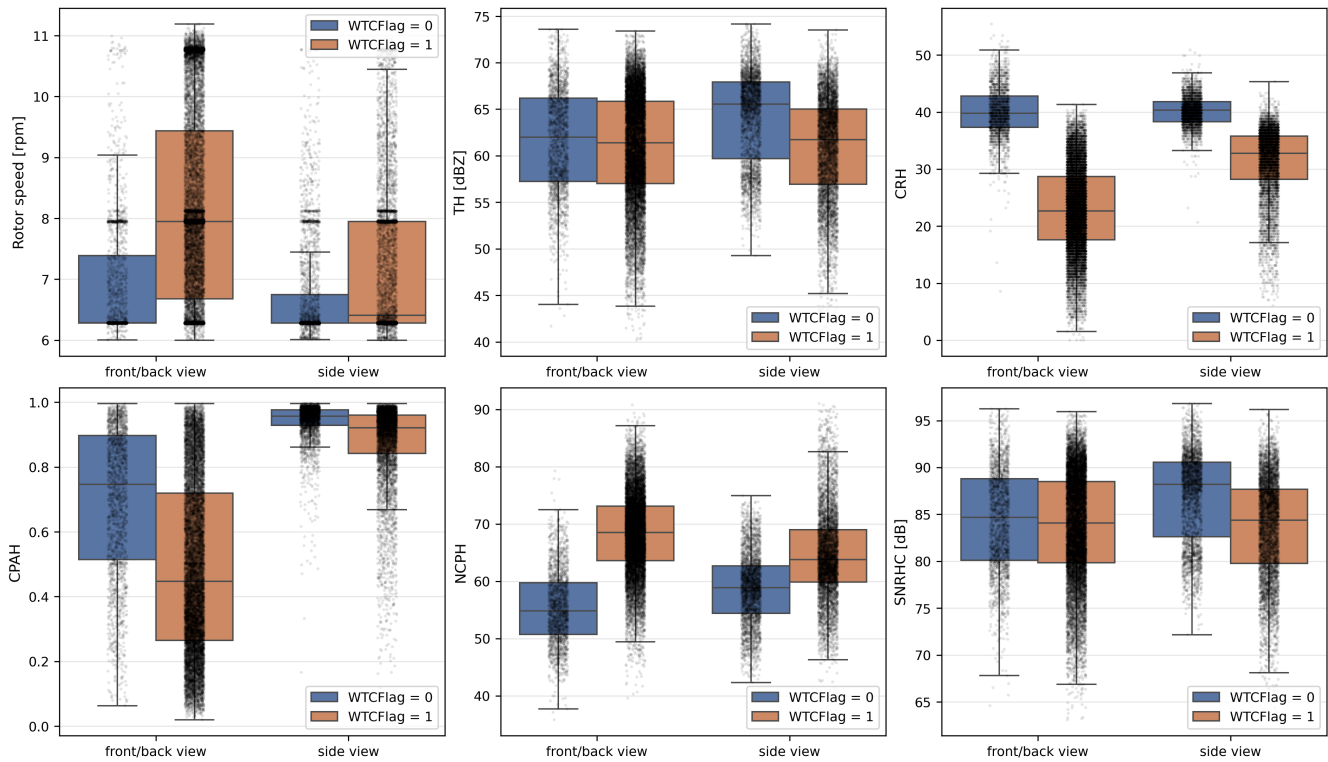


Figure 7. Comparison of selected radar-derived parameters and co-located turbine operating variables from turbine b0020171 stored in the WTC database, based on data written every 5 min during the operational volume scan at an elevation of 0.5° and including the WTC-Flag, the turbine operating parameter averaged rotor speed, and the radar moments uncorrected reflectivity (TH), clutter ration (CRH), clutter phase alignment (CPAH), non-coherent power (NCPH), and signal-to-noise ratio (SNRH) from the wind-turbine pixels Gönnebek. The analysis was restricted to the two main viewing geometries, front/back ($\alpha \geq 20^\circ$) and side view ($\alpha \geq 70^\circ$), and to high-rotor-speed cases (rotor speed > 5 rpm). Boxplots show the distributions for each view class and WTC-Flag, with individual samples overlaid in black. 20,684 cases were analyzed from September 2025 to August 2026.

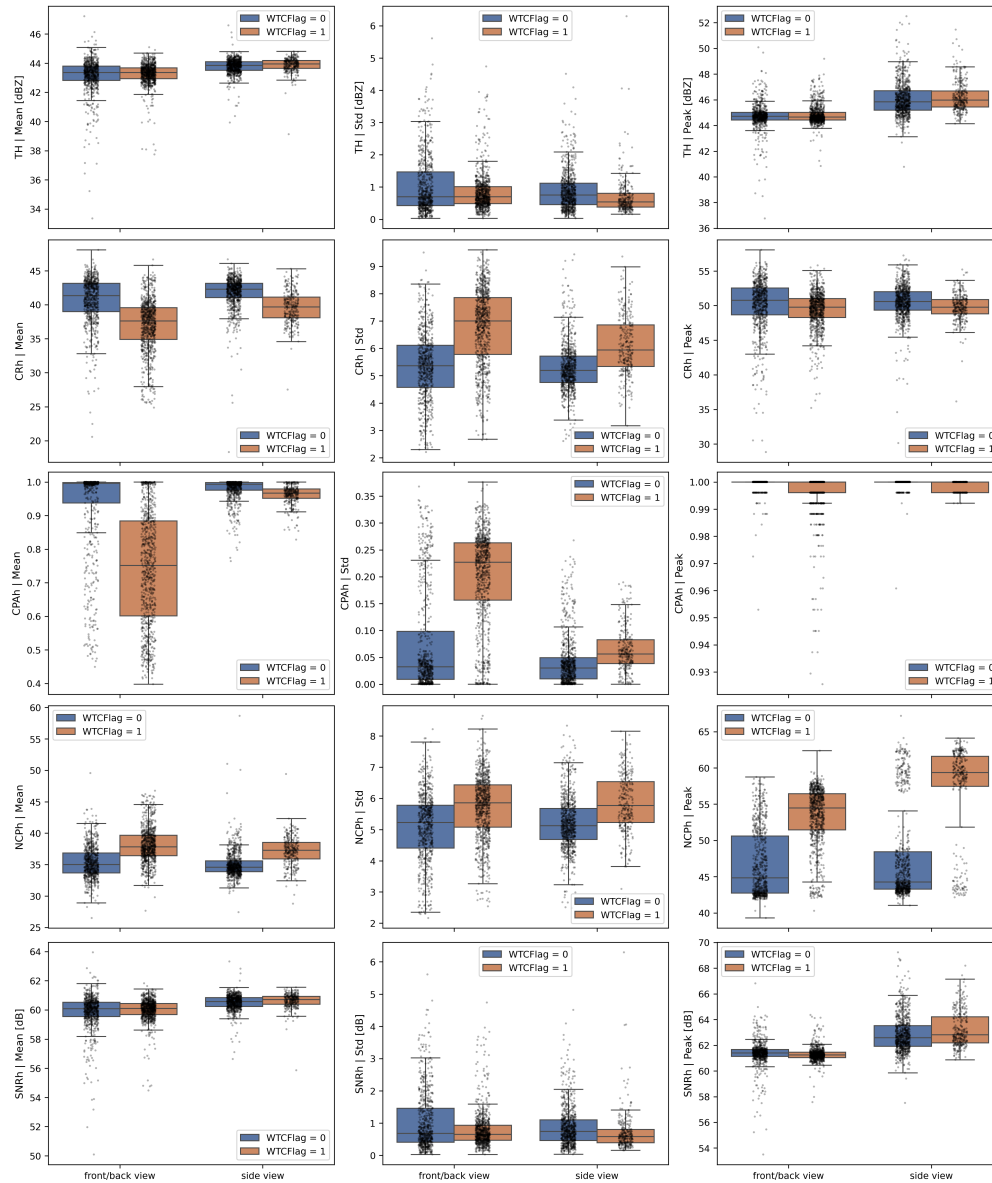


Figure 8. Comparison of summary descriptors of radar moments derived from dedicated spotlight-mode scans toward turbine b00171. In contrast to the operational volume scan, each spotlight-mode scan dwelled on the turbine for approximately 10 s, yielding a short time series of the turbine echo. For each dwell period, the radar moments uncorrected reflectivity (Th), clutter ration (CRh), clutter phase alignment (CPAh), non-coherent power (NCPH), and signal-to-noise ratio (SNRh) from the wind-turbine pixel were summarized at the turbine range by the mean, standard deviation and peak value. Each spotlight-mode scan was matched to the nearest operational volume scan, from which the corresponding WTC-Flag was taken. The effect direction remained stable under downsampling. Only a few peak- and variability-based descriptors, namely CRh peak, CPAh peak, NCPH mean, NCPH std, and partly CRh std, showed reduced robustness when comparing WTC-Flag=0 and 1, although the overall tendency between the two viewing geometries remained consistent. 2,499 cases were analyzed from June and July 2026.

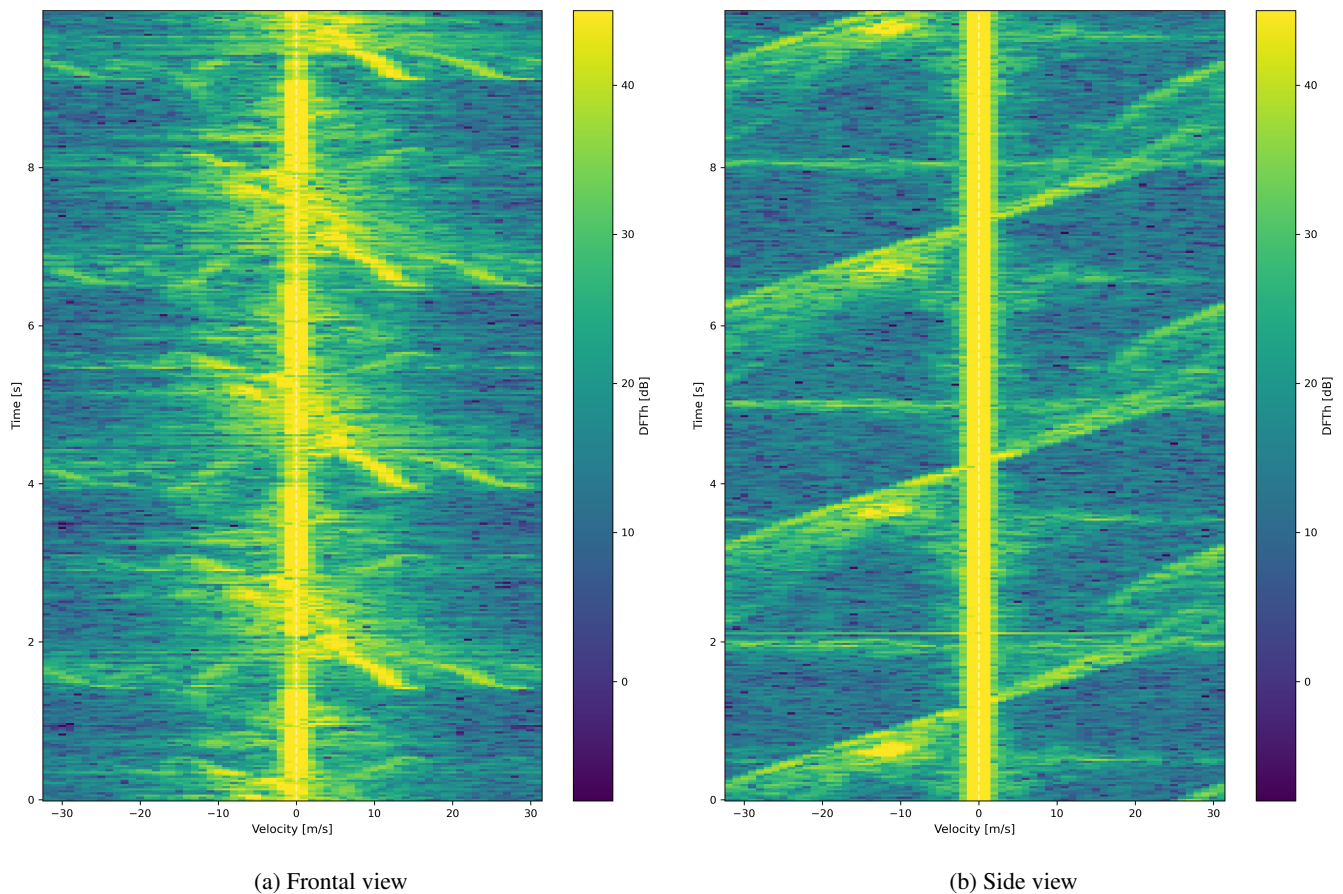


Figure 9. Doppler spectra from spotlight-mode scans of wind turbine b00171. The left panel shows a frontal-view case, while the right panel shows side-view case. The frontal-view example corresponds to 2026-05-15 22:24:49 UTC, with turbine state online, rotor speed 7.7 rpm, pitch angle -0.1° , nacelle orientation 218° , relative alignment in regards to the radar 164.3° , wind speed 6.8 m s^{-1} , and wind direction 222° . The side-view example corresponds to 2026-04-22 16:04:50 UTC, with turbine state online, rotor speed 7.7 rpm, pitch angle -0.1° , nacelle orientation 315° , relative alignment in regards to the radar -98.2° , wind speed 5.8 m s^{-1} , and wind direction 312° .



for both WTC-Flag classes, with mean values of 0.94 and 0.87 for $WTC - Flag = 0$ and $WTC - Flag = 1$, respectively, compared with 0.69 and 0.49 in front/back view. High CPAh values close to one indicate stationary ground clutter owing to its low backscatter-phase variability. Hubbert et al. (2009) found that approximately 77% of the examined clutter returns had CPAh values exceeding 0.90, whereas noise and weather echoes exhibited values below 0.5. At the same time, CPAh appears more variable in front/back view, as reflected by the larger spread of the corresponding distributions. Taken together, these results indicate that front/back detections are more strongly linked to turbine activity and to algorithmically relevant WTC signatures, particularly reduced CRh and enhanced NCPh. In side view, rotor speed is markedly less discriminative and the radar moments remain closer to fixed-clutter-like conditions. The much weaker rotor-speed dependence in side view is consistent with the directional behaviour shown in Figure 5 and suggests that the higher rate of missed detections in this geometry cannot be explained by lower turbine activity alone. This raises the question whether the differences found in the operational WTC database reflect genuinely different radar-moment characteristics of detected and non-detected turbine echoes for both viewing classes, or whether they are partly caused by the sampling strategy of the operational volume scan. During a volume scan, the radar beam only sweeps across the turbine for a short time. If wind-turbine echoes are intermittent, as suggested by the spectral “flashes” reported by Gabella et al. (2023) and Isom et al. (2009), the observed radar moments may depend strongly on whether the beam samples the turbine during such a flash or in between two flash events. In that case, $WTC-Flag = 0$ and $WTC-Flag = 1$ cases could differ not only because the underlying turbine signature is different, but also because the operational scan samples different phases of a rapidly varying radar return.

2.6.2 Radar-moment signatures in spotlight-mode scans

The operational WTC database contains only one set of radar-moment values per turbine observation and therefore cannot resolve the temporal evolution or Doppler spectral structure of the echo. Because the operational radar moments represent temporal averages, short-lived variations and intermittent signatures may be averaged out or masked. To provide temporal and spectral context for the operational WTC-Flag, we analysed dedicated spotlight-mode scans directed at turbine b00171 at an elevation of 0.6° . These observations continuously sampled the turbine echo for approximately 10 s and thus provided a short time series for each observation. Each spotlight-mode scan was matched to the nearest operational volume scan, from which the corresponding WTC-Flag and turbine operating parameters were obtained. No independent WTC-Flag was calculated from the spotlight-mode data, because the purpose of this analysis is to characterise the radar signatures associated with the operational detection decision. The extended dwell time allows radar-moment means, variability, and peak values, as well as Doppler spectral descriptors, to be compared between operationally detected and non-detected cases. The spotlight-mode observations thus provide temporal and spectral context for the operational WTC-Flag.

A total of 7,953 spotlight-mode scans were acquired in June and July 2026. Restricting the analysis to scans with rotor speeds exceeding 5 rpm and the relevant viewing geometries (front / back view and side view) yielded 2,499 scans for evaluation. From each 10 s dwell period, summary descriptors (mean value, standard deviation and peak value) were calculated of



the radar moments Th , CRh , $CPAh$, $NCPH$ and $SNRh$ at the turbine range (see Figure 8). Peakiness quantifies how strongly the dominant peak stands out from the background level of the spectrum. It is computed as the difference between the peak value and the spectral floor. This allows us to test whether the moment differences seen in the WTC database are also visible when the turbine is observed continuously over several seconds, and whether they are expressed mainly as changes in the mean state or as enhanced variability and intermittent peaks. The spotlight-mode analysis shows that several of the signatures seen in the operational WTC database persist under continuous sampling, but also reveals important differences in how the two viewing geometries are expressed over the 10 s dwell period (Figure 8). A downsampling analysis was conducted to assess the statistical stability of the results and showed good overall agreement for most descriptors. Only a few peak- and variability-based metrics (CRh peak, $CPAh$ peak, $NCPH$ mean, $NCPH$ std, and partly CRh std) showed reduced stability in the comparison between WTC-Flag = 0 and 1, although the overall geometric tendency remained unchanged. For Th the operational volume scans had suggested only limited geometric differences, whereas the spotlight-mode scans show a clearer separation. In side view, mean and peak Th are higher (mean: 44 dBZ vs. 43 dBZ; peak: 46 dBZ vs. 45 dBZ), while the within-scan standard deviation is lower by 0.1 dBZ, indicating a stronger but temporally more stable reflectivity signal during the dwell period. A similar contrast between mean level and temporal variability is found for $CPAh$. Mean $CPAh$ is markedly higher in side view, reaching near-saturation in both WTC-Flag classes ($WTCFlag = 0$: 0.98; $WTCFlag = 1$: 0.96), whereas front/back view remains around ($WTCFlag = 0$: 0.93; $WTCFlag = 1$: 0.74). Peak values are close to 1.0 in both geometries and thus contribute little to geometric discrimination. The main difference lies in persistence rather than maxima: side-view echoes stay near saturation much longer, while front/back echoes fluctuate more strongly, as reflected in the larger standard deviation (≈ 0.22 vs. ≈ 0.07). This is consistent with the operational scan results, where $CPAh$ was also systematically higher in side view but more variable in front/back view. For CRh , peak values are similar in both viewing geometries, reaching about 50, whereas the mean is higher in side view ($WTCFlag = 1$: 39.6 vs. 37.0) and the variability lower ($WTCFlag = 1$: 6.1 vs. 6.8). Thus, side-view echoes spend more time in a clutter-like high- CRh regime, whereas front/back view shows a more intermittent alternation between clutter-like and turbine-affected states. The $NCPH$ results from the spotlight-mode scans are especially revealing: mean values are similar overall, but peak $NCPH$ is clearly higher in side view, indicating brief, intense “flash-like” events rather than a sustained clutter signal. This is consistent with intermittent spectral flashes observed by Gabella et al. (2023) and Isom et al. (2009). Such brief peaks may be missed more easily by the operational volume scan, which samples the turbine only momentarily, even though they are clearly visible in spotlight-mode observations. A related pattern is found for $SNRh$, where side view shows a slightly higher mean ($WTCFlag = 1$: 60.6 vs. 60.0 dB), lower variability ($WTCFlag = 1$: 0.71 vs. 0.79 dB), and higher peaks (63.2 vs. 61.3 dB). Thus, side-view echoes combine a stronger and more stable signal level with higher instantaneous maxima, consistent with the larger spread in front/back view from the operational-scan result (see Figure 7) and the $NCPH$ results from the spotlight-mode scans. This again suggests that the continuous spotlight-mode observations capture short-lived amplitude enhancements that are not fully represented in the 5 min volume-scan sampling. In summary, the front/back geometry is the one in which algorithmically relevant mean-state shifts, in particular reduced CRh and enhanced $NCPH$, are most clearly expressed and thus most consistently detected by the operational algorithm. By contrast, side-view echoes often remain closer to a clutter-like mean state, with persistently high CRh and near-saturated $CPAh$, while still producing



pronounced but short-lived peaks in NCPH, Th, and SNRh. The lower detection rate in side view therefore does not necessarily indicate weaker turbine echoes, but rather a less favourable temporal and spectral distribution of the signature. Side-view cases tend to produce locally intense, temporally concentrated flashes, whereas front/back cases more often produce broader that are easier for the operational algorithm to detect. Figure 9 illustrates the contrast between side- and frontal-view Doppler spectra. Side-view spectra exhibit thin, well-separated flashes, whereas frontal-view spectra show broader, more diffuse signatures. In the operational 5 min scan, only a single spectral snapshot is available. Thus, the algorithm detects a disturbance only if the Doppler noise floor is sufficiently elevated. In frontal-view spectra, broad disturbances persist across many time steps, whereas in side-view spectra the residual flashes are either very fine horizontal lines, which are less likely to be sampled, or diagonal clutter lines, which affect only part of the spectrum and do not necessarily raise the noise floor sufficiently.

This interpretation is supported by an analysis of the Doppler spectra from the spotlight-mode scans with the doppler based spectral descriptors shown in Figure 10. For the front/back viewing geometry, the spectra of cases with and without a WTC-Flag differ systematically. WTC flagged cases show a distinct modification of the non-zero Doppler spectral power, with a larger fraction of power outside the near-zero Doppler region and a more even distribution of this power across Doppler velocity bins compared to the no WTC flagged cases. This is reflected by higher normalized entropy and a lower top-10 % power share. It indicates a broader and less concentrated Doppler spectral signature for WTC flagged cases. In contrast, the side-view geometry shows weaker differences between WTC-Flag = 0 and WTC-Flag = 1 in the spotlight-mode spectra. Thus, outside the operational scanning sequence, the side-view spectra of detected and undetected cases appear more similar. This suggests that, for side-view cases, the occurrence or absence of a WTC-Flag is less clearly controlled by a systematically different spectral shape. Instead, the detection is likely more sensitive to timing effects, for example whether a short-lived blade-related spectral feature is sampled at the relevant moment during the operational scan. Front/back-view signatures are more frequently detected by the WTC algorithm because their disturbance is broader, while side-view signatures are more easily missed because they are concentrated in short-lived spectral features. Front/back-view WTC detection appears to be governed mainly by the strength and structure of the turbine signature in the radar data, rather than by scan timing alone. Rotor speed supports this interpretation. The WTC-flag fraction increases with rotor speed for both viewing geometries. However, the increase is steeper for front/back views, which also reach higher detection fractions (see Appendix B Figure B3). This suggests that higher rotor speeds strengthen the broader front/back Doppler disturbance, whereas side-view detections remain more likely influenced by short-lived, timing-dependent features.

2.7 Pitch-angle dependence

The pitch angle characterizes the aerodynamic blade setting of the turbine and is therefore relevant for assessing whether turbine control affects WTC detectability. As shown in Figure 12, it is strongly skewed toward small angles, with most observations between about -2° and 4° , whereas larger pitch angles above 10° are rare. Pitch angles near 90° correspond to idle mode. Within this dominant operating range, the fraction of WTC detections decreases moderately from about 0.88 at -2 to 0° to 0.79 at 4 to 6° , but remains high overall. At intermediate pitch angles of roughly 6° to 10° , detection rates rise again

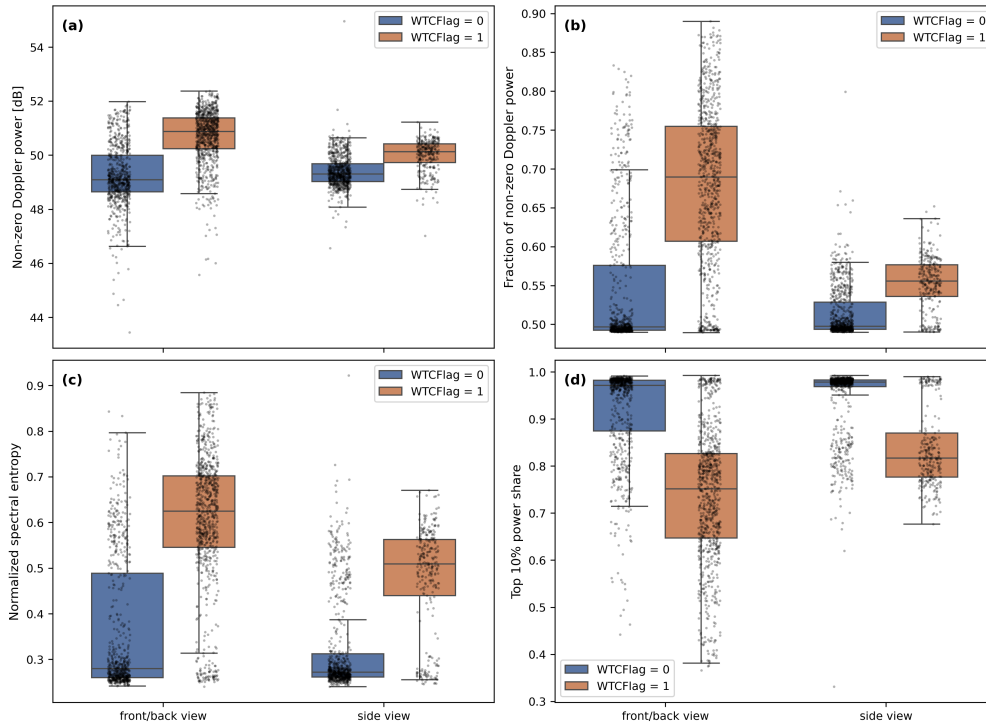


Figure 10. Distribution of non-zero Doppler spectral power for the selected representative spotlight-mode DFT spectra at the turbine range. The near-zero Doppler velocity region ($|v| < 0.5 \text{ m s}^{-1}$) was excluded before calculating the metrics. Panels show (a) the absolute non-zero Doppler power, (b) the fraction of spectral power outside the near-zero Doppler region, (c) the normalized entropy of the non-zero Doppler power distribution, and (d) the fraction of power contained in the strongest 10 % of non-zero Doppler bins. 2,499 cases were analyzed from June and July 2026.

above 0.86, while uncertainties increase due to the limited sample size. In Figure 12 (b) the dependence of pitch angle on rotor speed is evaluated. Roughly 29 % of observations correspond to near-idle conditions with rotor speeds of at most 1 rpm, while roughly 70 % occur at rotor speeds of at least 6 rpm, representing normal operation. Only 1.6 % fall into the intermediate range between 1 and 6 rpm. This scarcity indicates that the turbine passes rapidly through this transitional regime. During start-up, the pitch angle decreases rapidly above approximately 1 rpm, whereas during shut-down it increases more gradually as the rotor speed falls toward 6 rpm. Approximately half of the pitch angle observations between 1 and 6 rpm can be associated with a defined change of the WT operation mode which have on average a duration of 45 s and 90 s. This shows that the operation mode transition occur on a timescale substantially shorter than the 5-min radar sampling interval. Rotor speed and pitch angle are strongly linearly related, with about 94 % (R^2) of the variance in pitch angle explained by rotor speed alone. To assess the nonlinear dependence, a gradient-boosted decision-tree regression model (Friedman, 2001) using rotor speed as the sole predictor was fitted and evaluated on an independent 25 % test subset. The model achieved an out-of-sample coefficient of determination of $R^2 \approx 0.99$, indicating that pitch angle is almost entirely predictable from rotor speed within the analysed

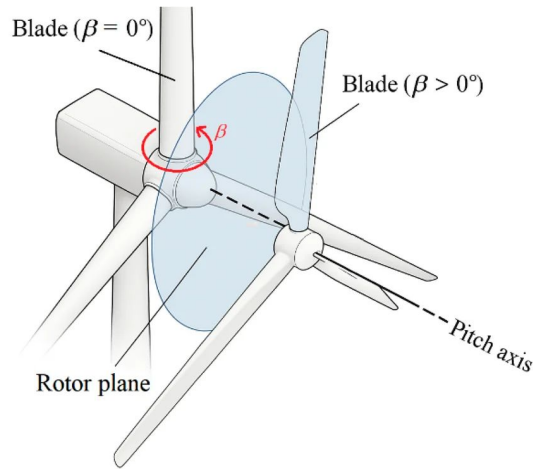


Figure 11. Schematic illustration of blade pitch control for a horizontal-axis wind turbine, adapted from Musuroi et al. (2025). The pitch angle β describes the rotation of the rotor blade about its longitudinal pitch axis. A pitch angle of $\beta = 0^\circ$ denotes the reference position aligned with the rotor plane, whereas $\beta > 0^\circ$ indicates a pitched blade configuration.

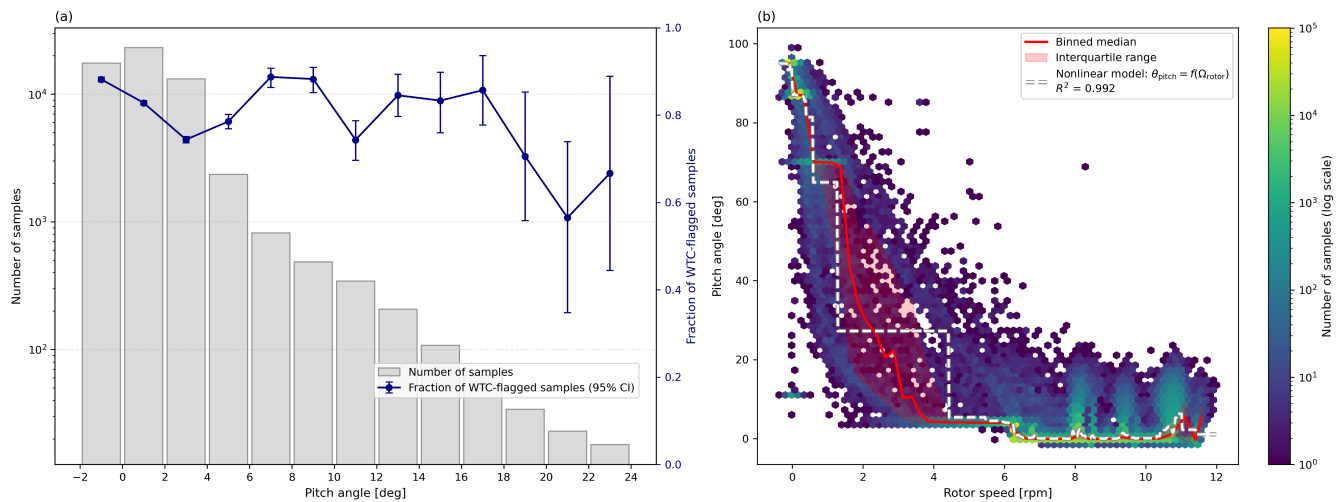


Figure 12. (a) Variation of WTC detection probability with pitch angle for all twelve turbines. The grey histogram shows the pitch-angle distribution with logarithmic scale, while the blue curve with 95 % bootstrap confidence intervals indicates the fraction of WTC flagged samples in each pitch-angle bin. (b) Relationship between rotor speed and pitch angle. The background shading shows the sample density on a logarithmic scale, the red curve denotes the binned median pitch angle, the shaded red area marks the interquartile range, and the dashed white curve shows the nonlinear rotor-speed-only model fit.



dataset. The pitch angle–rotor-speed relationship is not strictly one-to-one. Plume-like regimes at approximately 8.10, 10.75, and 10.90 rpm show varying pitch angles at nearly constant rotor speed, largely explained by wind-speed differences. These structures can largely be explained by differing wind speeds, with higher wind speeds being associated with higher pitch angles. As WTC detection remains above 80 % across wind-speed classes, pitch angle appears to reflect the operating state rather than independently affecting detectability at high rotor speeds. These results are consistent with Gabella et al., 2023, who identified rotor speed as a key predictor of backscattered-power characteristics, their variability, and the phase behaviour of horizontal and vertical polarizations. Gabella et al. (2023) also noted that blade pitch angle may change on timescales much shorter than the available 600s turbine-data sampling interval. The present analysis supports this interpretation: start-up and shut-down transitions through the intermediate 1–6 rpm range last, on average, less than 2 min. Overall, however, these short transitions contribute comparatively little to the dataset and are not resolved by the radar sampling interval. For WTC detection, pitch angle therefore appears to be of secondary importance relative to rotor speed. The future applicability of pitch angle information should not be discounted for other use cases, since features with limited standalone relevance may still contribute useful information in combination with other predictors, particularly in data-driven approaches especially in machine learning (Yu and Liu, 2004).

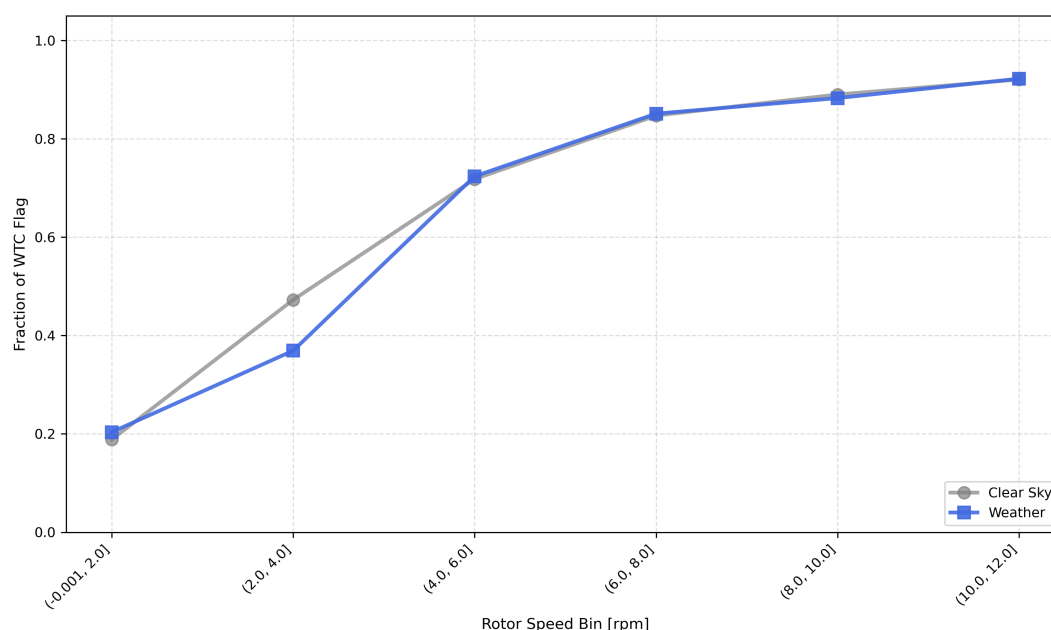


Figure 13. WTC-Flag detection rate per rotor speed bin for clear-sky (grey) and weather conditions (blue) for all twelve Gönnebek turbines.



2.8 Influence of weather conditions

To assess the influence of atmospheric conditions on WTC detection, the probability of precipitation versus clear-sky conditions was estimated using a fuzzy-logic approach applied to a 5×5 pixel subset from the 1.5° elevation. For selected radar parameters (see Appendix A) fuzzy membership functions with lower and upper transition zones and a central core representing maximum membership were defined. A weighted combination of these memberships yielded a probabilistic assessment of weather presence, with only time steps exceeding $P \geq 60\%$ considered. The parameterization explicitly accounted for ground clutter, biological targets, and increased reflectivity and texture under clear-sky conditions at this elevation. The resulting fuzzy-logic-based probabilities of precipitation versus clear-sky conditions were then used to analyze WTC detection in the 0.5° elevation scan, retaining only cases with a precipitation probability of at least 60% or a clear-sky probability of at least 60%, thereby excluding ambiguous and low-quality cases. Fuzzy parameter definitions and weights are detailed in the Appendix. Samples classified as either clear-sky or weather conditions consisting of more than 179,000 observations in the 0–12 rpm range, with approximately two-thirds classified as clear-sky conditions and one-third as weather conditions. Results indicate that WTC detection is generally higher under precipitation, with mean WTC-Flag fractions exceeding those under clear-sky conditions across all turbines (e.g. b00172: 0.60 vs. 0.52). To isolate the influence of atmospheric phenomena from the operational state of the turbines, a stratified analysis was conducted by binning the data according to rotor speed (see Figure 13). The results demonstrate that rotor speed acts as a primary confounding variable. WTC detection appears to be largely independent of weather conditions, with the observed detection rates being primarily governed by the turbine's rotational velocity. When controlling for rotor speed, the disparity in detection rates between weather and clear-sky conditions becomes statistically negligible (e.g. $\Delta = 0.4\%$ in the predominantly populated 6–8 rpm bin). Consequently, the data confirms that the detection algorithm is highly robust in a range of precipitation situations.

3 Conclusions

This study quantified the main drivers of WTC detectability in operational DWD C-band weather radar measurements. The analysis uses co-located turbine operator data and radar observations from the Gönnebek wind farm near the Boostedt radar, complemented by dedicated spotlight-mode scans of one turbine. The detection algorithm is based on the elevated noise floor in the doppler spectrum of WTC. It is not sensitive to weather condition. The evaluation confirms the results from Frech et al. (2026) that rotor speed is the dominant turbine operating parameter controlling operational WTC detectability. Detection probability increases strongly with rotor speed. The radar-relative nacelle orientation also influences detectability. Front- and back-view geometries show higher and more robust WTC detection rates, whereas side-view geometries exhibit substantially more missed detections. Operational radar moments show that front/back detections are associated with clearer algorithm-relevant signatures, especially reduced clutter ratio and enhanced non-coherent power. Dedicated spotlight-mode scans reveal that side-view turbine echoes are not necessarily weaker, but often more intermittent. WTC flagged front/back-view cases show a larger fraction of non-zero Doppler power and a broader, less concentrated distribution across Doppler velocity bins. In side view, differences between WTC-Flag = 0 and 1 are weaker, consistent with more localized and intermittent spectral flashes. The



directional dependence of WTC detectability is governed not only by echo strength, but by the temporal and Doppler-spectral distribution of the turbine signature. Flashes from side view cases may be missed by the operational volume scan. Having identified rotor speed and radar-relative nacelle orientation as the main determinants of WTC detectability, we also assessed whether blade pitch provides additional explanatory information. It shows only limited independent explanatory power, but may still be useful in combination with other applications, especially in data-driven detection or correction approaches. The temporal aggregation analysis shows that 5 min aggregated turbine data are sufficient for the present WTC-Flag-based validation. Aggregation to 10-15 min, however, begins to remove relevant information. Other applications may still benefit from high resolution data.

The Gönnebek results are based on one year of observations and a large number of cases. The bootstrap confidence intervals provide an estimate of the sampling uncertainty and generally support the robustness of the observed patterns. The results can therefore be regarded as representative for the investigated wind farm, and similar patterns may be expected in a subsequent year. Nevertheless, the comparison with Laichingen demonstrates the scientific value of applying the approach to further wind farms. The rotor-speed dependence, as well as the high WTC detection probability for frontal viewing geometries and its decrease towards side-view geometries, is consistent between Gönnebek and Laichingen. In contrast, the approximately symmetric directional behaviour observed at Gönnebek, with increasing detection probabilities for rear-facing orientations, is not reproduced at Laichingen. This difference may result from site-specific conditions, turbine design, and the radar measurement geometry, including the influence of static clutter. Analyses of additional sites, turbine models, and radar viewing geometries are therefore needed to distinguish generally transferable features of WTC detectability from site- and turbine-specific effects. In addition to validating the present method across a wider range of sites and turbine configurations, future work should focus on extending the detection approach itself. The detection approach should be extended to account for turbine-induced effects in dual-polarimetric radar variables, since the affected polarimetric volume can extend beyond the area currently identified by the WTC-Flag.

Real-time turbine operational data substantially improve the interpretation of radar signatures. In particular, rotor speed and nacelle orientation provide essential context for site-specific impact assessments and for validating or refining WTC quality-control procedures. Our results support impact assessments that consider turbine operation and radar-turbine geometry in addition to distance. They also support the conclusion of Frech et al. (2026) that the immediate radar environment within 5 km should remain protected from wind-turbine development, because strong clutter signatures and their associated radar-data impacts may not be reliably identifiable from operational radar observations alone. Future work will extend WTC detection towards turbine-affected dual-polarimetric moments. Further mitigation methods are being investigated within the WICLEAN project.



Appendix A: Fuzzy parameter definitions and weights

Table A1. Fuzzy membership parameters used for the weather and clear-sky probability estimation. The four nodes (x_1, x_2, x_3, x_4) define the trapezoidal membership function.

Probability	Variable	x_1	x_2	x_3	x_4
Weather	DBZH _{mean}	-15.0	-5.0	60.0	75.0
Weather	UDR _{mean}	-64.0	-32.0	-8.0	0.0
Weather	URHOHV _{mean}	0.80	0.90	1.00	1.02
Weather	SQI _{mean}	0.10	0.30	0.90	1.00
Weather	SNR _{mean}	-5.0	0.0	20.0	30.0
Weather	DBZH _{std}	0.0	0.2	2.0	4.0
Weather	CPA _{std}	0.0	0.2	2.0	5.0
Clear sky	DBZH _{mean}	-35.0	-25.0	0.0	8.0
Clear sky	UDR _{mean}	-12.0	-8.0	-3.0	1.0
Clear sky	URHOHV _{mean}	0.60	0.65	0.85	0.98
Clear sky	DBZH _{std}	6.0	8.0	16.0	25.0

Table A2. Weights used for the fuzzy weather and clear-sky probabilities, together with the classification thresholds and temporal matching interval.

Category	Parameter	Value
Weather	w_{DBZH}	0.35
Weather	w_{UDR}	0.10
Weather	w_{URHOHV}	0.25
Weather	w_{SQI}	0.05
Weather	w_{SNR}	0.05
Weather	$w_{\text{DBZH, std}}$	0.10
Weather	$w_{\text{CPA, std}}$	0.10
Clear sky	w_{DBZH}	0.40
Clear sky	w_{UDR}	0.15
Clear sky	w_{URHOHV}	0.25
Clear sky	$w_{\text{DBZH, std}}$	0.20
Threshold	$\text{TH}_{\text{weather}}$	0.6
Threshold	$\text{TH}_{\text{clearsky}}$	0.6



Appendix B: Rotor speed dependence of WTC detection by viewing geometry.

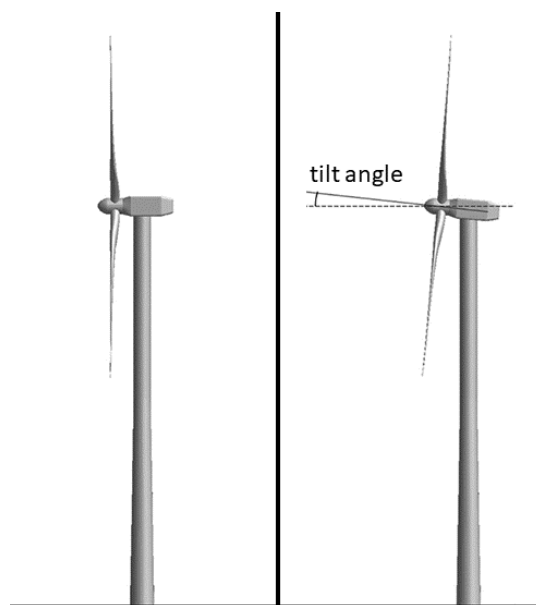


Figure B1. Illustration of wind turbine without (left) and with tilt angle (right) (adapted from Santo et al., 2020).

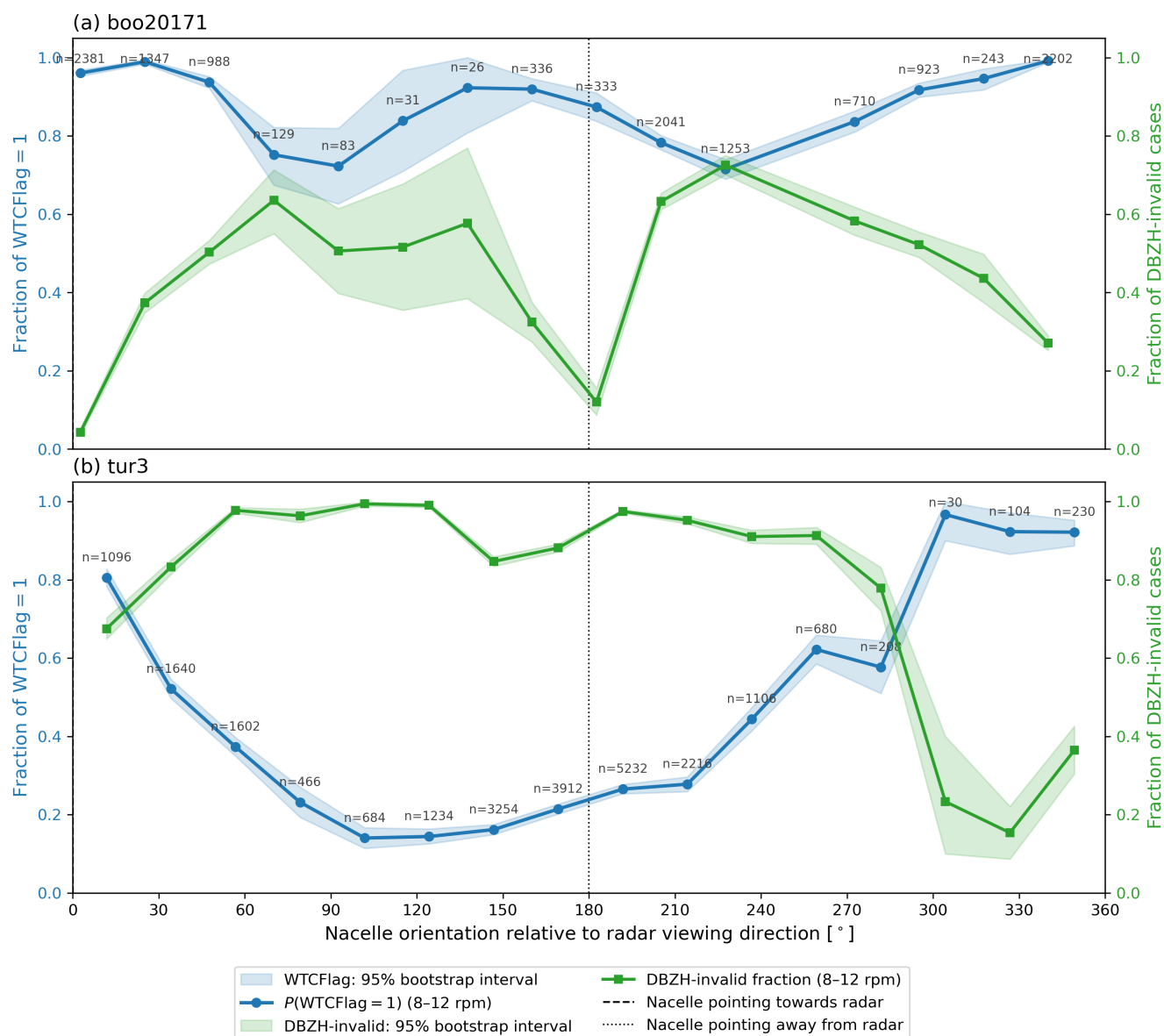


Figure B2. Fraction of WTC detections (WTC-Flag = 1; blue line, left axis) and fraction of cases with invalid DBZh observations (green line, right axis) as a function of nacelle orientation relative to the radar viewing direction. Results are shown for rotor speeds between 8 and 12 rpm. The upper panel (a) shows turbine `boo20171` from Gönnebek wind farm and the lower panel (b) shows turbine `tur3` from Laichingen wind farm (Frech et al., 2026). Shading indicates the 95 % bootstrap confidence interval for the WTC-Flag and invalid DBZh fractions. Numbers indicate the number of valid WTC-Flag observations in each 22.5° nacelle-orientation bin; bins with insufficient data are omitted. A relative orientation of 0° indicates that the nacelle points towards the radar, whereas 180° indicates the opposite direction.

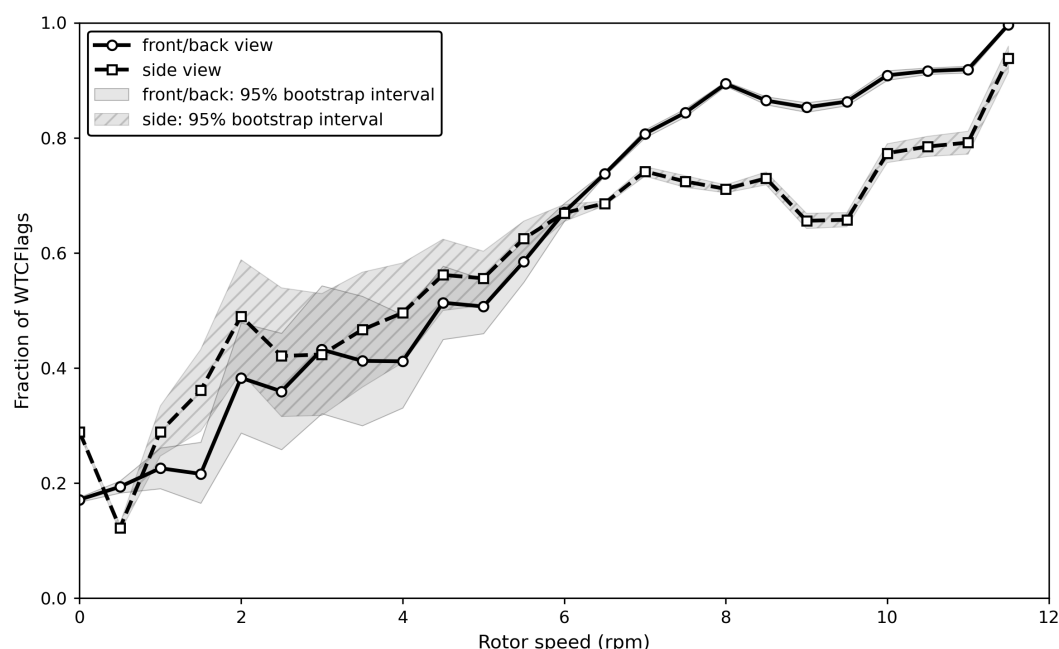


Figure B3. Fraction of cases with and without a WTC-Flag as a function of rotor speed, separated by viewing geometry for all twelve turbines. The analysis comprises 196,339 front- and back-view cases and 186,491 side-view cases. Solid lines show front/back-view cases and dashed lines show side-view cases. The WTC-flag fraction increases with rotor speed in both geometries, but the increase is more pronounced for front/back-view cases at higher rotor speeds. Shading indicates the 95 % bootstrap confidence interval.

460 *Code and data availability.* Radar data used in this work, that is not available through opendata.dwd.de, can be provided upon request. Python code used for the analysis are available upon request.

Author contributions. MH conducted the analysis and prepared the manuscript, with contributions from AB, MF, and MT.

Competing interests. There are no competing interests.

465 *Acknowledgements.* This work is supported by the Federal Ministry for Economic Affairs and Climate Action on the basis of a decision by the German Bundestag: project WICLEAN, Wivaldi Wind Turbine Clutter Experiment and Analysis, grant number 03EE2074A. Special thanks go to the operator of the twelve turbines near Boostedt radar and the operator of the two wind turbines near the Türkheim radar system

<https://doi.org/10.5194/egusphere-2026-5570>

Preprint. Discussion started: 2 October 2026

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for providing the wind turbine operator data. GPT-5.4, GPT-5.5 and GPT-5.6 were used as supportive AI tools for language formulation and programming assistance. Scientific analysis, results, and final manuscript content were authored and reviewed by the authors.



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