

Comparative Analysis: Multi-Sensor Approaches for Bird Collision Monitoring at Offshore Wind Farms

Technical Whitepaper

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Summary

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Executive summary

This document outlines the design concepts and strategic implementation of sensor technologies, **Radar**, **Long-range** and **Short-range cameras**, to monitor bird activity and collision risks in offshore wind environments. While individual systems have inherent limitations, their integrated use creates a comprehensive data collection framework.

Spoor recommends long-range cameras as a critical component due to their ability to provide behavioural tracking over high coverage volumes, accurate interaction data, and time coverage of at least 96%.

In the Reference Environment of the German North Sea, long-range cameras maintain high performance because high migratory bird movement is reduced by approximately 80% during periods of low visibility (which occur only 1.5% - 4% of the time). Consequently, the potential for undetected migratory activity is limited to just 0.3% - 0.8%.

Internal modelling shows that a nacelle-based approach observes 73% of the rotor zone, while a tower-based approach observes 61%. Therefore, short-range cameras cannot fully eliminate coverage gaps caused by structural occlusion.

Comparison of approaches

Radar, long-range and short-range cameras systems bring specific strengths and weaknesses to biodiversity monitoring in offshore wind . This document outlines those strengths and weaknesses and presents the design concepts of both long- and short-range cameras systems which may complement and mitigate the shortcomings of Radar when gathering data to assess the risk of operating offshore wind turbines to migrating bird populations.

Radar provides the best level of continuous spatial coverage but is weak for identification of the bird species (radio waves do not capture visual characteristics used for identification) and for capturing movement close to the turbine (radio waves are reflected from the turbine surfaces resulting in high noise in the immediate surrounding area of the turbine). Radar is good for collecting general bird activity data, as well as macro- and meso-avoidance if deployed for that purpose and is unaffected by most weather, though heavy rain and snow may impact detections due to the 'noise' created by the weather conditions.

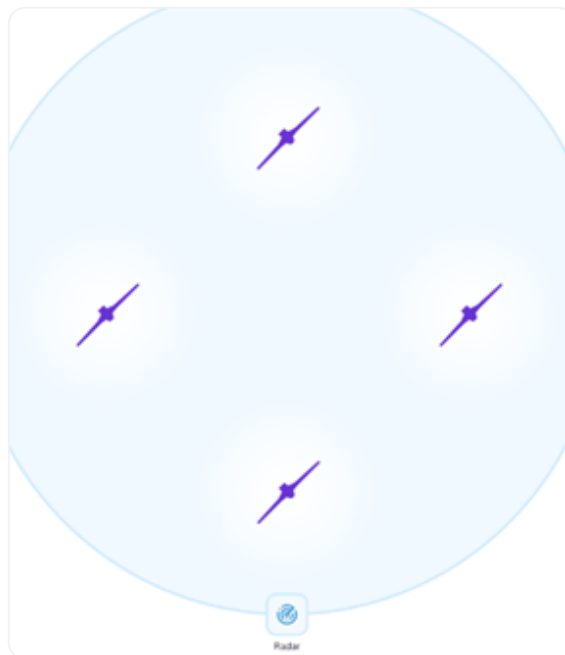


Figure 1: Radar coverage of wind farm

Long-range stereo cameras provide a high level of continuous spatial coverage around the turbine rotor swept zone. This approach is best for providing complete coverage of the rotor swept zone due to two camera perspectives, and for capturing micro-avoidance behaviour close to the turbine. Due to the high volume of airspace covered, long-range cameras provide a high baseline for correlation of bird detection with Radar, increasing confidence in the data. Performance may be diminished in low-visibility conditions, though in low-light /night-time conditions, infrared illumination may be used to provide the contrast required to

detect birds at night. Performance for the detection of small birds is dependent on both the camera location and specification

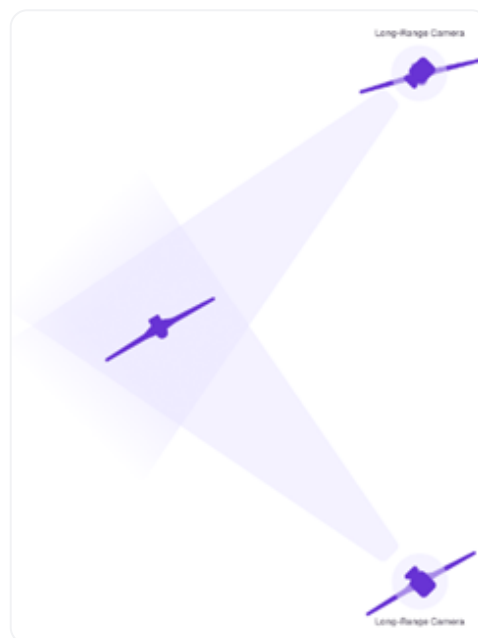


Figure 2: Long-range stereo cameras

Short range cameras provide continuous coverage of a turbine's rotor swept zone from a closer perspective. This approach provides confidence that small bird or objects flying close to the turbine will be picked up on camera. Due to their positioning on the turbine itself, short-range cameras are impacted by occlusion by the turbine structure itself. This means detection of collisions on the face of the turbine rotors, or on the 'blind' side of the nacelle or tower cannot be visually confirmed by the camera on the other side. Short-range cameras provide a low coverage volume (due to short focal lengths and depth of field) and so coverage exists mostly within the blind spot of a radar system with little to no overlap with the airspace covered by radar. This means that whilst some detections and interactions are captured, the ability to confidently correlate the detection data with the radar data can be limited. In low visibility conditions, close-range cameras may still make detections, however in extremely low-visibility conditions such as heavy rain or snow, occlusion of even short-range cameras can prevent detections. Please refer to the Spoor document "*Short-range camera bird detection concepts*" for a detailed technical description of these claims.



Figure 3: Short-range camera array

The characteristics of each monitoring method are summarised in Table 1, below:

Feature	Radar	Long Range Camera	Short Range Camera
Detection Volume and Range	Radar covers the widest area of all continuous monitoring options	High. Long range cameras can detect objects at ranges up to 2000m and can cover volumes of ~27million m ³ per camera	Low. Shorter focal lengths provide a wider field of view to cover the rotor area at the expense of depth of field, resulting in a low volume of coverage and low detection range.
Species ID	Weak. Radar cannot use visual indicators to detect species. Wingbeat frequency and flight heights may be used as indicators but can be error prone.	High. Visual indicators, flight track patterns and bird size are used to classify the bird. High volume coverage also enables this approach to classify a larger proportion of the bird population.	Best. Visual indicators and flight track patterns are used. Due to closer proximity, birds should theoretically be easier to classify with higher resolution images, though smaller birds at the periphery of the camera detection range may still prove problematic. Only birds that enter the camera field of view can be classified.
Heavy Rain / Snow	High Clutter, detections may be susceptible to noise	Occlusion, optical sensors can be degraded or blinded depending on density or rain/snowfall	Partial Occlusion, requires heavier density of rain/snowfall than long range but still susceptible to degradation.
Low Light / Night	No impact. Radio waves unaffected.	Requires illumination Detection range	Requires illumination Detection range dependent on IR illumination range, but

		dependent on IR illumination range	shorter ranges easier to light up
Fog	No impact. Radio waves unaffected.	Susceptible. Lower visibility ranges will impact detection ranges	Limited. Performance drops but close in visibility may remain functional
Blind Spots	Turbine proximity.	Small birds. Sensitivity can drop off as distance and bird size decreases. Can be mitigated by higher camera resolutions, lenses and camera arrays but there is an effective ceiling.	Structure. Occlusion of bird detections, interaction and collisions will occur due to the physical structure of the turbine blocking visibility.
Correlation Potential	Baseline for meso- and some macro-avoidance behaviour. Baseline for detection and activity counts.	Overlapping monitoring volumes provides a high level of confidence in correlation, resulting in a higher quality data output	Little to no overlap in monitored volume with radar results in lower confidence in data quality due to bird activity data being collected inside the radar blind spot. Some overlap with long range camera is useful for collision validation.

Table 1: comparative strengths and weaknesses of monitoring methods

Synergies and correlation strategy

Whilst each method has specific strengths and weaknesses, when deployed in combination, each method can complement another's weak spots.

The optimal configuration from a purely technical perspective would be to apply all three methods, though this does not take practicality and cost into consideration (which this document does not discuss).

Combining two of the three approaches may address practicality and cost considerations, but this then involves making a trade-off decision for data collection. Assuming the radar system to be a fixed requirement, the synergies and trade-offs of each approach is summarised in the table below.

Combination	Strengths and Mitigation	Weak spots and gaps	Correlation Reliability
Radar & Long-range Camera	Accurate bird detection counts. Meso- and Micro-avoidance behaviour. High confidence bird turbine interaction data.	Diminished performance in low visibility can result in missed turbine interactions.	Good Confidence: High overlap in detection volumes enables data fusion and higher data quality. Tested offshore.
Radar & Short-range Camera	Easier to detect smaller birds and to Species ID all birds	Complete lack of micro-avoidance behaviour Occlusion by the turbine itself limits detection volume and visual confirmation of some collisions	Low Confidence: Low to no overlap in detection volumes results in lower data quality. Tested onshore only.
Radar & Long- and Short-range Camera	Best possible coverage Complete ' <i>chain of custody</i> ' across the three sensor types Highest resilience to low-visibility conditions	Cost (capital and operational), complexity (more points of failure and technical feasibility (nacelle mounted cameras, vendor warranty and accessibility)	High Confidence: Each sensor type overlaps with at least one other, increasing overall data quality and confidence. Neither tested offshore or onshore.

Table 2: Synergies and trade-offs between systems

Should a trade-off decision need to be made between choosing a long or a short-range approach, we can summarise this as sacrificing all bird micro-avoidance behaviour in and around the monitored turbine, vs. the ability to detect small birds interacting with the turbine during low visibility conditions. Additionally, only the radar and long-range camera system are currently tested offshore.

Trade-off details

When considering a trade-off, it is reasonable to examine the question as to which decision has the highest impact on the value of data collection. The sections below describe the factors we should consider when assessing the potential impact.

Migration of small birds during poor visibility conditions

It has long been acknowledged that birds time their migrations to coincide with favourable weather conditions (Lack 1960, Richardson 1978). An improved understanding of the link between weather conditions and migration which trigger migratory movements has been crucial to developing models to forecast migratory movements, with a view to developing measures to mitigate collision risk by curtailing turbines when migration intensity is greatest (Bradaric et al., 2020). Migratory movements have been closely linked to periods of good visibility (Lack 1960, Pyle et al., 1993), with analysis of radar data suggesting that migration intensity may be reduced by as much as 80% during foggy conditions (Panuccio et al., 2019). Furthermore, the conditions favoured by birds during migration, stronger tailwinds and higher ambient temperatures (Sinelschikova et al., 2007), are those under which foggy conditions are less likely to develop.

Hüppop note that collision rates at offshore platforms coincide with periods of adverse weather conditions, which they describe as including periods of strong wind and low visibility, which may be linked to heavy rain, drizzle, or fog. However, they note that the strong correlation between conditions onshore and those offshore in the German EEZ mean that the likelihood of night during which conditions are both favourable for migration, and riskiest in relation to collisions with offshore structures, is low. Additionally, the data collected by Hüppop et al., (2016) demonstrated that even on nights during which circumstances align to create the greatest risk of collisions, overall numbers can remain low, even with a high abundance of birds, determined using acoustic monitoring. This highlights the potential for birds to avoid collisions, even during apparently risky conditions. More detailed investigations of the movements of migrating birds during such conditions highlights behavioural changes, which are likely to reduce collision risk. These include birds reversing course and returning to land (Pastorino et al., 2017, Kirsch et al., 2015), or increasing their flight altitude to well above heights typical of modern turbines when encountering foggy conditions (Pettersson 2011).

Reference Environment – The German North Sea^[1]

The German open North Sea has been selected as the reference environment for this analysis due to its extensive history of offshore wind development and the availability of robust, long-term meteorological data. As a high-traffic corridor for migratory birds, it provides a benchmark for assessing the effectiveness of sensor systems in offshore environments. The climatic dynamics and visibility thresholds observed here are considered representative of the operational challenges faced by offshore wind clusters more generally.

Climatic Dynamics of the Open North Sea

The meteorological characteristics of the open North Sea differ significantly from coastal regions. Areas situated approximately 50 km offshore, such as the vicinity of the Borkum Riffgrund, typically exhibit a lower susceptibility to dense fog compared to the coastline. This is primarily attributed to the reduced influence of landmasses, higher average wind speeds, and more robust atmospheric vertical mixing (Bundesamt für Seeschifffahrt und Hydrographie [BSH], n.d.). Despite these factors, fog remains a regular phenomenon, particularly during nocturnal hours and within the transitional seasons of spring and autumn.

Statistical Frequency and Visibility Thresholds

Long-term climatological data provided by the Deutscher Wetterdienst (DWD) and various European meteorological services indicate that the German Bight experiences an average of 20 to 30 fog days per year. Most of these events are concentrated during the night and early morning hours (DWD, n.d.).

Recent research into offshore atmospheric conditions has further refined these statistics regarding visibility. While fog is frequent, "dense fog"—defined by a visibility range of less than 200 meters—is a rarer occurrence, often persisting for only a few hours during a recorded fog day.

Nocturnal Dense Fog Projections

Based on the integration of BSH maritime atlases and specific offshore studies, the area 50 km off Borkum typically encounters 5 to 15 days per year of nocturnal dense fog. On an annual basis, this represents a frequency of approximately 1.5 % to 4.0 %. These values are subject to interannual variability; "fog years," characterized by stagnant air masses and high humidity, may see frequencies exceeding these averages (DWD, n.d.).

^[1] This data was compiled via AI-assisted data analysis

Avoidance behaviour and statistical correlation

Bird collision data are crucial for assessing the impact of wind farms on avian populations. To properly contextualize collision rates, it is necessary to consider bird movements and avoidance behaviours at three scales: macro, meso, and micro (Cook et al., 2018, May, 2015).

Radar systems are best suited for capturing macro- and meso-avoidance statistics and sampling in-farm bird activity. Integrating data from radar and long-range cameras can improve data quality through cross-validation at the meso-level. This cannot be performed reliably with short-range cameras because the detection range and volume of these cameras provide an insufficient overlapping baseline on which to correlate. Micro-avoidance is essential to accurately assess collision risk, as it relates the number of collisions to birds entering the risk zone (see figure 4).

Using only radar and short-range cameras may miss critical micro-avoidance data due to limited coverage. Relying on radar and long-range cameras risks underreporting small bird collisions in low-visibility conditions, but this accounts for only 0.3–0.8% loss of migratory coverage due to limited low-visibility periods.

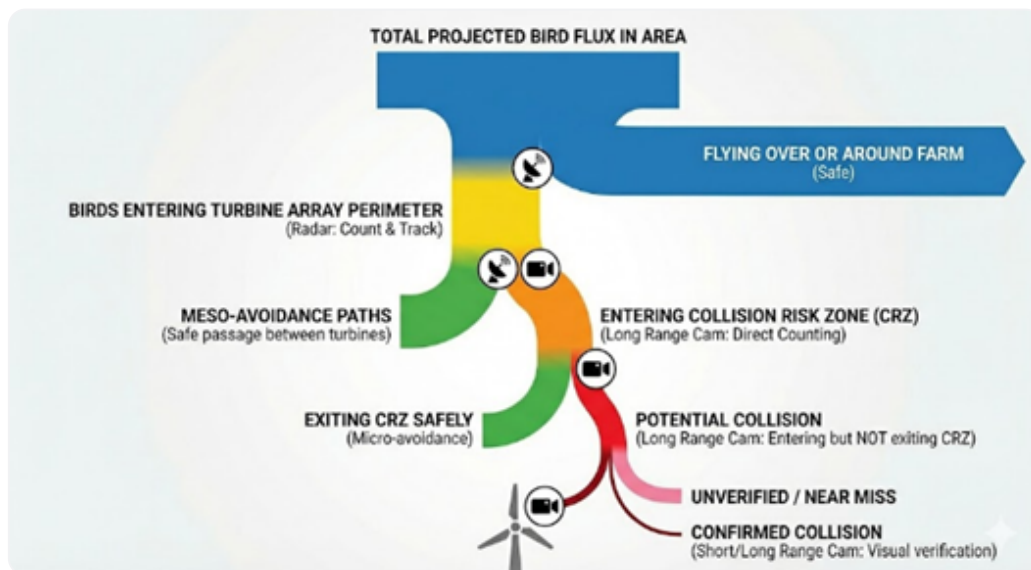


Figure 4: Collision count in context

Summary

Proceeding with a radar plus short-range camera-based approach risks losing critical micro-avoidance statistics that are required to place the collision data in the context of the overall impact of the wind farms impact on bird populations. The lack of volume coverage of the short-range approach cannot compensate for the absence of coverage in the surrounding airspace of the turbine.

Proceeding with a radar plus long-range camera-based approach means that during periods of low visibility (1.5 % - 4 %), the likelihood of high migratory bird movement is reduced by approximately 80%. As a result, the potential for undetected migratory activity during these times is only 0.3 %–0.8 %, hence a very small amount of the migration period is not covered by long-range cameras. The long-range cameras yield beneficial and reliable results as they are recording continuously during day and night functioning at least 96 % of the time, capturing general flight activity data, correlated meso- and micro-avoidance behaviour, as well as potential collisions from multiple points of view.

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