Executive Summary

Wind Farm Layout Impact on Radar Performance

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WIND FARM LAYOUT IMPACT ON RADAR INTERFERENCE EXECUTIVE SUMMARY

Wind turbines are a known source of radar interference due to their large static towers and fast-moving rotor blades which generate radar returns that can confuse traditional clutter processing. Various mitigation approaches involving upgraded radar equipment, advanced signal processing, and infill radars have been previously studied, and are still pursued by government and industry stakeholders due to promising initial results. The focus of this study, however, was the question of whether radar impact can be prevented or significantly limited from the onset by favoring certain wind farm layout characteristics in the construction of new wind farms.

In order to investigate how wind farm layout features affect the magnitude of wind-turbine-related degradation of radar performance, a statistical analysis relating radar performance metrics and wind farm layout measures was conducted. Data from twelve Airport Surveillance Radars Model 11 (ASR-11s) and six Common Air Route Surveillance Radars (CARSRs) with extended signal processing[1] was collected over a period of twelve days in December, 2018. The two radar types within this study represent two variations of above-wind-farm clutter processing algorithms: spatial and temporal signal thresholding, respectively. Reinforcement rates, false alarm rates, and track drop rates in regions above 86 wind farms in these radars' line-of-sight were computed. Five types of layout characteristics were calculated for all the wind farms considered: range to radar, visibility, wind farm size, wind farm density, and non-wind-turbine-occupied space within the wind farm. Statistical models were fit to the data seeking to explain the three performance metrics through different combinations of wind farm layout characteristics. An objective model selection process was then applied to find the best-fitting, but not over-fitted, and intuitive models, for each radar performance measure.

The wind farm layout based models obtained in this study explain up to 73% of variation in radar performance with the worst-fitting model still achieving a fit of 46%. Reinforcement rate and track drop models display better fits and predictive power than models for false alarm rates. Wind farm distance, visibility, density, and empty space metrics either occur in models across the board directly or correlate to the other model variables selected, suggesting that these wind farm layout characteristics are indeed significant drivers of above-wind-farm radar performance for all radar types considered. In particular, evidence was found that once a construction area has been selected and range and visibility of wind turbines are predetermined to a large degree, adjusting wind farm density and the distribution of non-wind-turbine-occupied space with respect to the radar detection grid (the range-azimuth bins by which the radar processes detections) is promising in reducing false alarm rates and improving aircraft tracking above wind farms. The following list summarizes the wind farm layout parameters that were found to be strong predictors of radar impact.

- **Distance between wind farm and radar.** For both radar types considered, a larger distance between the radar and the wind farm correlated with improved reinforcement rates and fewer

[1] Other CARSRs with a large wind turbine presence in their vicinity are expected to have the updated signal processing capabilities of the CARSRs in this study enabled in the future.

track drops. A reduction in false alarm rates was also observed for CARSR wind farms further removed from the radars.

- **Visibility of wind farm.** A larger median visible portion of wind turbines within a farm corresponded to lower reinforcement rates for both radar types. The false alarm rates and track drop rates of ASR-11s were negatively impacted as well. Additionally, a high number of visible wind turbines was a predictor of lower reinforcement rates and higher track drop rates for ASR-11s.
- **Areal density of wind turbines.** ASR-11s and CARSRs displayed reduced reinforcement rates and increased track drop rates in the airspace above wind farms with denser wind turbine placement.
- **Density with respect to radar detection grid.** For ASR-11s, denser wind turbine placement with respect to the radar detection grid corresponded to reduced false alarm rates. For CARSRs, placing multiple wind turbines into a single radar cell may decrease the radar's efficiency in suppressing returns from the wind turbines. However, it may still be beneficial to reduce the number of wind-turbine-occupied cells overall and should be evaluated on a case by case basis.
- **Inclusion of empty radar detection cells within wind farm area.** For ASR-11s, the increased separation of wind turbines through unoccupied radar detection cells within the wind farm area correlated to a reduction in track drops. This suggests that in such cases the radar is able to track a target by receiving aircraft position updates from between wind turbines even if detections from directly above wind turbines are lost. For CARSR's, increases in non-wind-turbine occupied radar cells within the farm were not observed to significantly improve radar performance directly, however they would still correspond to a reduced areal density of the wind farm which would reflect positively on radar performance.

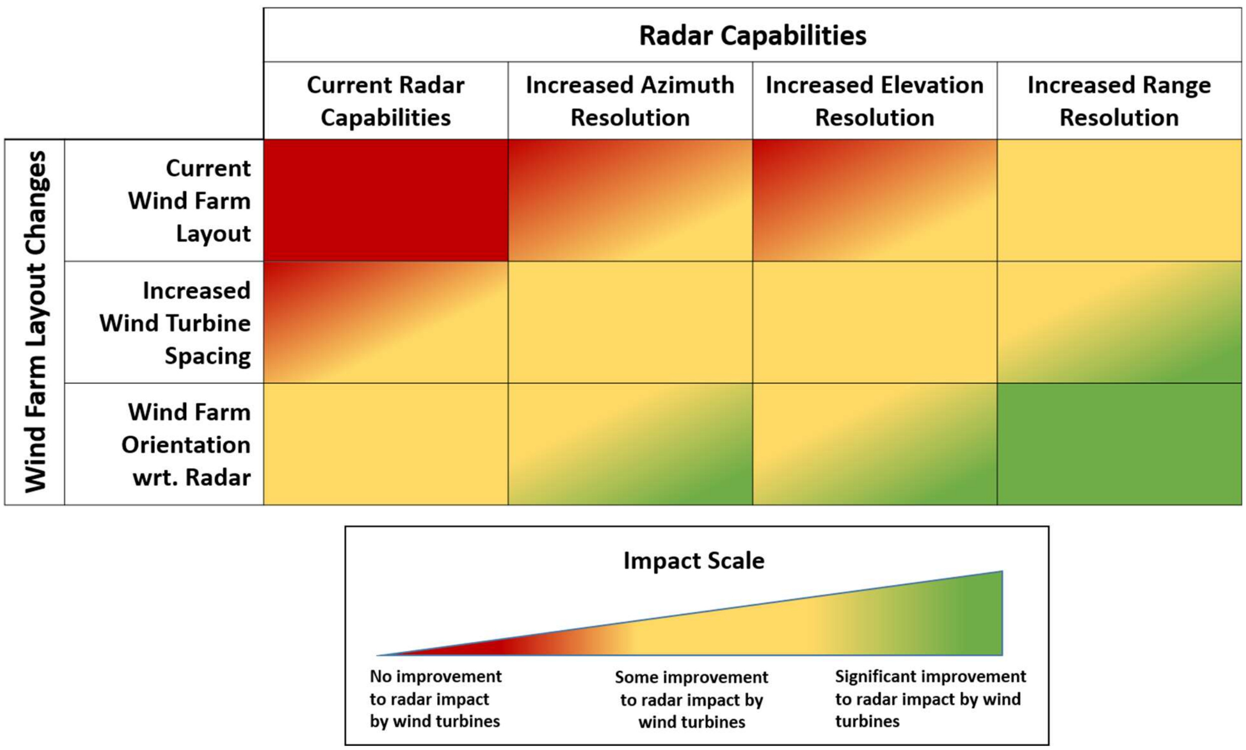
It is important to note that aside from the wind farm layout features, each radar's settings, the particulars of the radar-wind farm geometry and surrounding landscape, as well as site-specific wind farm clutter mitigation approaches play a role in determining how well the radar performs above a particular wind farm. Hence, models found within this study are not suited to make exact predictions of radar performance above any future wind farm. Their purpose is rather in extracting the most influential layout metrics and estimating their average impact on radar performance.

Since wind turbine sizes are likely to grow and necessitate wider spacing of wind farms in the future, and since radar capacity to mitigate wind turbine clutter is likely to improve, a portion of this study was dedicated to the question of which changes in wind farm layout and radar capabilities are likely to have the biggest impact on reducing the challenges associated with wind farm development near future radar sites or near current radars that may be updated with advanced clutter processing.

To answer this question, different wind farm layouts and varying radar range resolution capabilities were contrasted against each other via a simple model. It was found that while tracker performance is likely to improve due to increased wind turbine spacing combined with improved signal processing, most significant benefits can be achieved with radar-centric wind farm layout and radars operating at higher bandwidth. In particular, the comparison between above-wind-farm radar performance at 1MHz, 5 MHz, and 10 MHz of instantaneous bandwidth revealed that increases in range resolution have significant potential to alleviate the degradation in performance due to wind turbine clutter. Additional benefits to radar performance could be obtained if wind farm orientation with respect to the radar could be optimized by placing wind turbines in rows and columns in certain angles relative to the radar. TABLE 1 summarizes the projected impacts of changes in wind farm layout as well as future radar capabilities.

TABLE 1

Assessment of Effects of Changes in Wind Farm Layout and Radar Upgrades



GLOSSARY

ASR-11	Airport Surveillance Radar Model 11
CARSR	Common Air Route Surveillance Radar
False alarm	A radar detection not generated by an intended surveillance target. Depending on system settings, an air traffic controller may see a target on the operator screen where no aircraft is present.
Radar grid	A discretized version of the radar's field of view. For the purpose of signal processing, the radar's surroundings are broken down into range and azimuth bins. Radar detections are processed based on their origin within the radar grid.
Reinforcement rate	The rate at which the primary radar is able to detect targets detected by the co-located beacon radar.
Signal thresholding	Radar detections below certain signal strength levels are rejected based on dynamically computed signal thresholds.
Track drop rate	Rate at which radar detection processing and target tracking software has to cease updating the information on target location and trajectory attributes due to non-available radar updates of the target or detections that are not recognized as target-associated. This implies that an air traffic controller losses sight of the target on the operator screen at least temporarily.