

Methodology for Assessing the Impact of Wind Turbines on Civil Aviation Primary and Secondary Radars

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Context

Obstacles



Logistics Buildings



Solar panel fields



Wind farm

Impact

Primary Radar

- Retrodiffusion: saturation
- Masking: modification of the gain pattern
- Multipath: ghost echoes

Secondary Radar (cooperative target)

- Masking: modification of the gain pattern, $\Sigma - \Delta$ processing
- Multipath: ghost echoes



Objectives

Study case

Objective: Quantify the impact of a unique wind turbine or a wind farm on radar signals

Why: large vacant lots often nearby airports (2 to 15 km far from the radar):

- Industrial point of view: large wind farm settlements
- Civil aviation point of view: maintain availability, continuity and security of radar services

Characteristics of the problem

- Primary and secondary radars at S and L-band respectively
- Wind farms seen as several vertical metallic cylinders, along the same radial or covering a larger azimuthal region
- Distance between radar and wind turbines of a few km
 - ⇒ Far-field assumption not verified at L-band frequencies
 - ⇒ RCS not valid

Outline

- ➊ *Radar antennas: near-field modelling*
- ➋ Electromagnetic modelling and assumptions
- ➌ Primary Radar
 - ➊ Retrodiffusion
 - ➋ Multipath
 - ➌ Masking
 - ➍ Case study
- ➍ Secondary Radar
 - ➊ Multipath
 - ➋ Masking
 - ➌ $\Sigma - \Delta$ processing
 - ➍ Case study
- ➎ Conclusion

Radar antenna modelling

Near-field modelling

Classical solutions

- Fine antenna modelling \Rightarrow important computation time
- Antenna Far-field modelling \Rightarrow not precise enough since obstacles can be closer than the Far-field distance

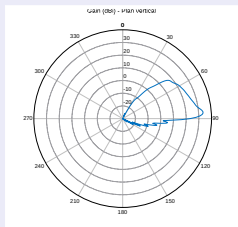
Alternative solution: Far-field to Near-field transform

Woodward-Lawson method

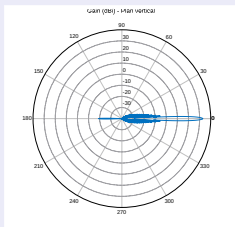
Far-field gain pattern both in vertical and horizontal planes

\Rightarrow Limited number of radiating current, defining an equivalent aperture

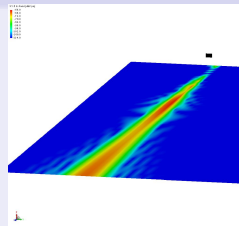
Example: Primary Radar



Vertical Gain Pattern (dBi)



Horizontal Gain Pattern (dBi)



Electric field value (dBV/m)
radiated by a radar located 1.5 m
high.

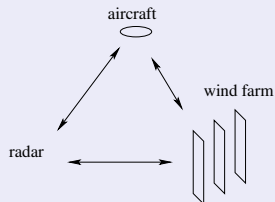
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Methodology for the electromagnetic modelling

Assumptions

Hypothesis: the radar points in the direction of a wind turbine



Far-field approximation

Interaction	distance	Validity
radar-wind turbine	from 1 km to 15 km	not validated
radar-aircraft	greater than a few km	validated
aircraft-wind turbine	greater than a few km	not validated

Scattered and total field

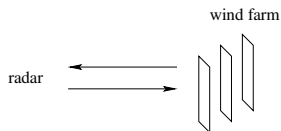
- Radar modelling: equivalent aperture
- Wind turbine modelling: physical optics (PO) assumption

⇒ Analysis of the scattered field, particularly on approach zones, runways and for the retrodiffusion on the radar ⇒ Analysis of the gain pattern in the radar main axis

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Primary radar: Direct retrodiffusion



Calculation of the scattered field echoes

- Distance radar-wind farm \Rightarrow Use of RCS not appropriate
- Calculation of the scattered field E
- Calculation of the received power P_r using

$$P_r = \frac{E^2 \lambda^2}{8\pi \zeta_0} G_b \text{ STC},$$

with G_b the antenna reception gain, STC is the Sensitivity Time Control, i.e. an additional attenuation for close echoes, $\zeta_0 \approx 120\pi$ is the vacuum impedance.

- In dBm

$$P_r \text{ dBm} = E_{\text{dBV/m}} + \text{STC}_{\text{dB}} + 30 + 10 \log \left(\frac{\lambda^2}{8\pi \zeta_0} G_b \right).$$

- Possible saturation of the primary radar if P_r is greater than the radar sensitivity P_{r0} (ex: -105 dBm).

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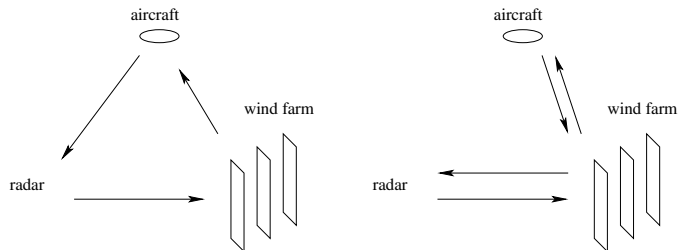
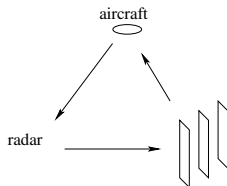


Figure: Possible multipath scenarii.

Modelling methodology

- Calculation of the scattered electric field at the aircraft
- Estimation of the received power at the radar following two scenarii:
 - ▶ radar \rightarrow wind turbine \rightarrow aircraft \rightarrow radar ;
 - ▶ radar \rightarrow wind turbine \rightarrow aircraft \rightarrow wind turbine \rightarrow radar.

Multipath 1: radar → wind turbine → aircraft → radar



Method

- Calculation of the electric field scattered by the wind turbine (PO)
- Modelling of the aircraft by its bistatic RCS σ_a
- Propagation towards the radar at a distance R
- Radar gain G_a in the direction of the aircraft

Received power

$$P_r = \frac{\|\mathbf{E}\|^2}{2\zeta_0} \sigma_a G_a \left(\frac{\lambda}{4\pi R} \right)^2,$$

Negligible impact if

$$\|\mathbf{E}\| < \frac{4\pi R}{\lambda} \sqrt{\frac{2\zeta_0 P_{r0}}{\sigma_a G_a}}, \quad \text{with } P_{r0} \text{ the radar sensitivity}$$

Multipath 2: radar → wind turbine → aircraft → wind turbine → radar.

Method

- Calculation of the electric field scattered by the wind turbine (PO)
- Reciprocity theorem, considering both following states:
 - ① The radar emits, the aircraft receives radar → wind turbine → aircraft ;
 - ② The aircraft emits, the radar receives aircraft → wind turbine → radar.

The reciprocity theorem imposes $P_e^{(1)} P_r^{(2)} = P_e^{(2)} P_r^{(1)}$ with

- ▶ $P_e^{(1)}$ the power emitted by the radar in state ①
- ▶ $P_r^{(1)}$ the power received by the aircraft in state ① $\Rightarrow P_r^{(1)} = \frac{\lambda^2}{4\pi} \frac{\|\mathbf{E}\|^2}{2\zeta_0}$
- ▶ $P_e^{(2)}$ the power emitted by the target in state ② $\Rightarrow P_e^{(2)} = \sigma_a \frac{\|\mathbf{E}\|^2}{2\zeta_0}$
- ▶ $P_r^{(2)}$ the power received by the radar in state ②

Final expression

$$P_r = \frac{\lambda^2 \sigma_a}{16\pi \zeta_0^2 P_e} \|\mathbf{E}\|^4.$$

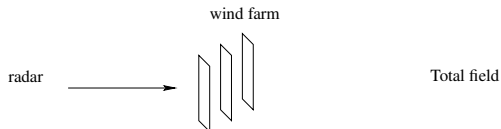
Negligible impact if

$$\|\mathbf{E}\| < \sqrt[4]{\frac{16\pi \zeta_0^2 P_e P_{r0}}{\lambda^2 \sigma_a}}$$

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Masking



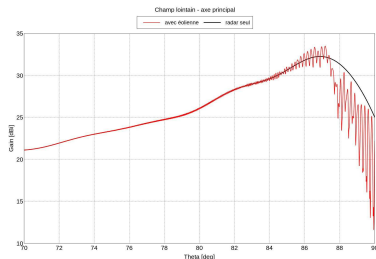
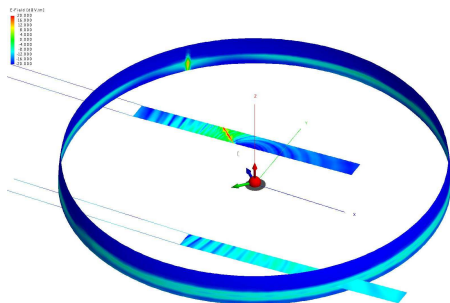
Method

- Calculation of the total electric field at 4 km around the radar and in far field, along the radar main axis, in the presence of a wind turbine (PO)
- Comparison to the nominal gain pattern, in dB

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Case study



Configuration

- **Radar** Radar Star NG, S-band (2750 MHz), 15 kW, 34 dBi maximum gain, 40 m altitude, STC = -20 dBm
- **Unique wind turbine** 100 m in height, 2.5 m in radius, no blades, distance to radar 1 km.
- **Radar direction:** towards the center of the wind turbine

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Multipath

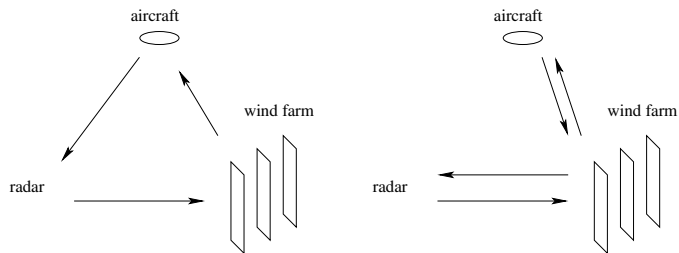


Figure: Possible multipath scenarii.

Modelling methodology

- Calculation of the scattered electric field at the aircraft
- Estimation of the received power at the aircraft transponder
- Two possible scenarii when the transponder answers:
 - ▶ radar → wind turbine → aircraft transponder → radar ;
 - ▶ radar → wind turbine → aircraft transponder → wind turbine → radar.
- Due to the directive gain pattern, second scenario more probable

Multipath 2: radar \rightarrow wind turbine \rightarrow aircraft transponder \rightarrow wind turbine \rightarrow radar.

Method

- Calculation of the electric field scattered by the wind turbine (PO) at the aircraft
- Comparison to the threshold of the aircraft transponder $P_{\text{transp}} = -74$ dBm.

Final expression

Considering $G_{\text{transp}} = 0$ dB

$$P_r = \frac{\lambda^2}{8\pi\zeta_0} \|\mathbf{E}\|^2.$$

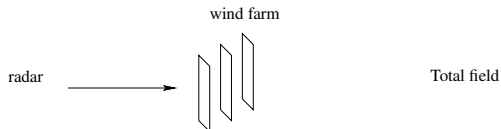
No transponder's answer if

$$\|\mathbf{E}\| < \frac{\sqrt{8\pi\zeta_0 P_{\text{transp}}}}{\lambda}.$$

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Masking



Method

- Calculation of the total electric field at 4 km around the radar and in far field, along the radar main axis, in the presence of a wind turbine (PO)
- Comparison to the nominal gain pattern, in dB

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$\Sigma - \Delta$ processing

Method

- Calculation of the total electric field (far field), along the radar main axis, in the presence of a wind turbine (PO), both for Σ and Δ patterns
- Calculation of the off-boresight angle error

Mathematical expressions

Off-Boresight Angle (OBA) in azimuth

$$OBA_{az} = \frac{\Re\{E_{\Delta}\}}{\Re\{E_{\Sigma}\}}$$

OBA error

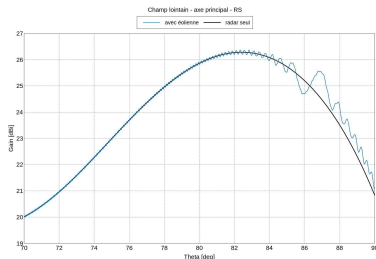
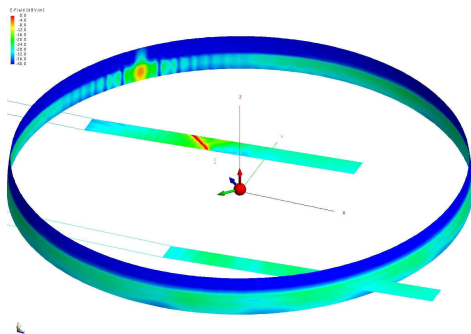
$$Err = OBA_{az} - OBA_0$$

with OBA_0 calculated without obstacle.

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Case study



Configuration

- **Radar** Radar AS909, L-band (1030 MHz emission, 1090 MHz reception), 2 kW, 28 dBi maximum gain, 43 m altitude
- **Unique wind turbine** 100 m in height, 2.5 m in radius, no blades, distance to radar 1 km.
- **Radar direction:** towards the center of the wind turbine

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Conclusion

Methodology

Methodology for Assessing the Impact of Wind Turbines on Civil Aviation Primary and Secondary Radars

- Modelling of the antenna near field
- Calculation of the scattered field using PO
- Direct retrodiffusion for primary radars
- Multipath and ghost echoes for primary and secondary radars

Future work

- Radar data treatment to be taken into account
- Coupling between wind turbines (student project on analytical formulation of the electric field scattered by cylinders)

Questions?