

# A Statistical Model for Assessing the Impact of Wind Turbines on Conventional VOR

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# Plan

- 1 Introduction
- 2 VOR Error Simulator
- 3 Probability Distribution for the Multipath Parameters
- 4 Statistics of the bearing error
- 5 Simulation
- 6 Conclusion

# Context

- Impact of large size obstacles, such as wind turbines, on VOR performances
- Multipath  $\Rightarrow$  Error in the azimuth assessed by the aircraft receiver

## Existing tools

### Two steps

- Computation of the multipath characteristics: magnitude, phase, azimuth  
 $\Rightarrow$  Electromagnetic simulation
- Computation of the bearing error  
 $\Rightarrow$  Use of the Odunaiya expression or a receiver model

### Example

- VERSO: VOR Error Simulator, developed by ENAC, funded by ENAC and DSNA

### Limitations

- Require high computationnal resources
- Require to perfectly know the configuration
- Results are highly dependant on the trajectory:  
Modification of the trajectory of order few meters  
 $\Rightarrow$  Change in the multipath phase  
 $\Rightarrow$  Change in the bearing error

# Objective

## Objective

Propose a statistical model for the bearing error with which

- The only parameters are the aircraft and wind turbine positions
- The other parameters (wind turbine size, materials, ground composition, ...) follow statistical distributions

## Main steps to develop this model

- Determine the statistical distributions associated with the multipath parameters
- Determine the statistical distribution associated with the bearing error
- Perform Monte Carlo simulations with VERSO to assess the parameters of the statistical distributions

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# General characteristics of wind turbines

## Windturbine characteristics

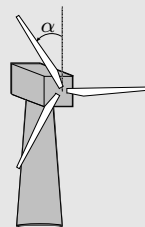
- Mast
  - Metallic with a possible reinforced-concrete lower part
  - Conical shape of height from 60 to 140 m
- Hub box
  - Metallic or dielectric, metallic generator
  - Ovoid or rectangular shape
- Blades
  - Multilayer dielectric : glass or carbon fiber, epoxy, mix of materials
  - Lightning protection thin metallic plate or wire



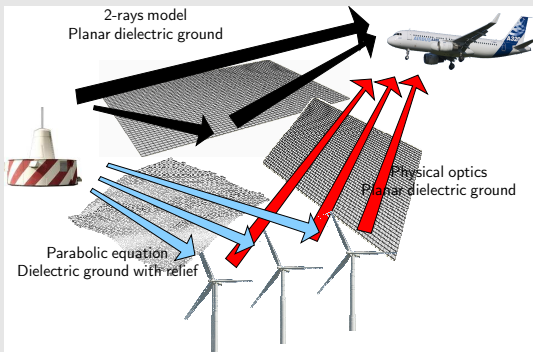
## Used model

- Mast: metallic conical section
- Nacelle: metallic rectangular box
- Blade: Simplified multilayer dielectric structure
- Lightning protection: metallic wire

Mesh: multilayer-slab or metallic polygonal facets



# VERSO : VOR ERror SimulatOr



## Input/output

### Input

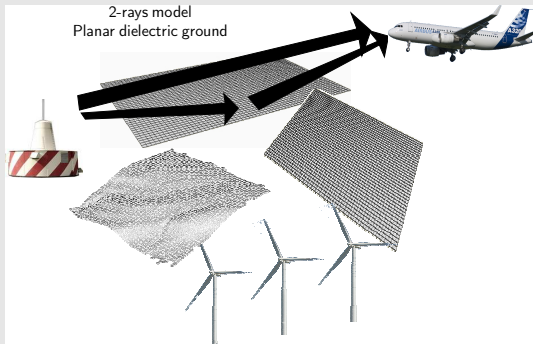
- VOR station position and radiation pattern
- Positions and characteristics of the wind turbines
- Relief
- Aircraft trajectory

### Output

- Scattered field
- VOR error



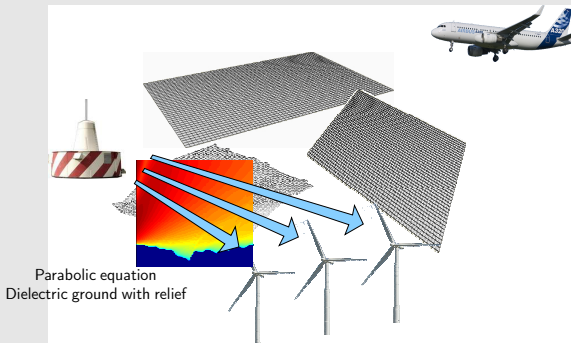
# VERSO : VOR ERror SimulatOr



## Two-rays model

- Take into account the ground in the VOR station antenna radiation
- Calculation of the direct path

# VERSO : VOR ERror SimulatOr



## Parabolic equation

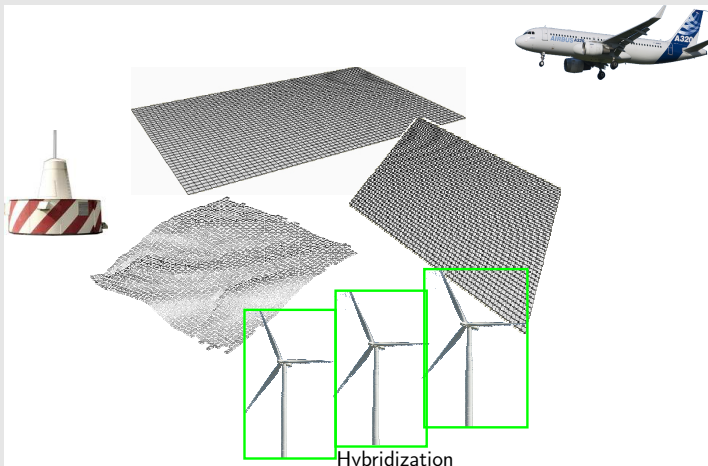
Model the propagation VOR station → wind turbines

⇒ Grazing incidence, significant influence of the ground relief

Split-step-Fourier parabolic equation method:

- The relief is accounted
- Only the Forward propagation is accounted
- 2D model (no lateral effect of the relief)
- Atmospheric refraction is accounted

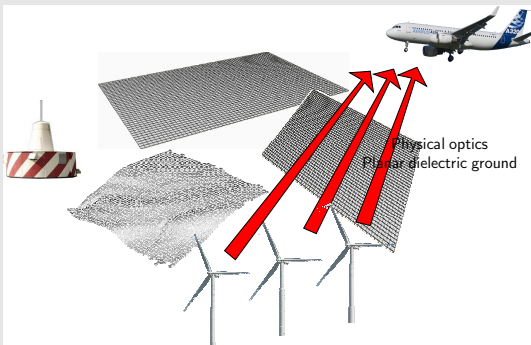
# VERSO : VOR ERror SimulatOr



## Hybridization

On each polygonal facet of the wind turbine, the incident field is interpolated as a plane wave

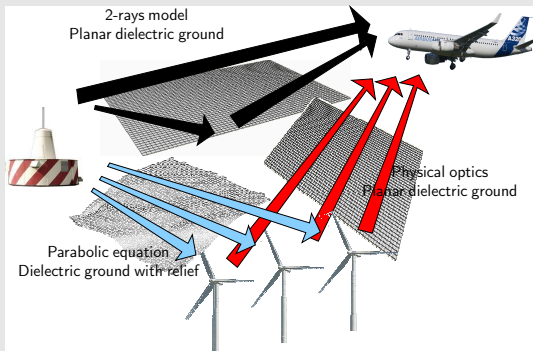
## VERSO : VOR ERror SimulatOr



## Physical optics

- Multilayer-slab or metallic polygonal facets with an incident plane wave
- Currents calculation using the physical optics approximation
- Fast calculation of the radiation integrals
- Hypotheses: large enough wind turbines, no multiple scattering, planar dielectric ground

# VERSO : VOR ERror SimulatOr



## VOR error

- Scattered field are clustered with respect to their azimuth of arrival  
 ⇒ List of multipath: amplitude  $a_n$ , phase  $\theta_n$ , azimuth  $\phi_n$
- Conventional VOR error formula (a similar formula exists for Doppler VOR)

$$\varepsilon^C = \tan^{-1} \left( \frac{\sum_{n=1}^N a_n \cos(\theta_n - \theta_0) \sin(\varphi_n - \varphi_0)}{a_0 + \sum_{n=1}^N a_n \cos(\theta_n - \theta_0) \cos(\varphi_n - \varphi_0)} \right)$$

# In-flight measurement campaign

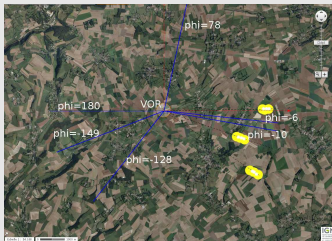


Figure 1: Windfarm located at 5 km from the VORC station in Boulogne-sur-Mer.

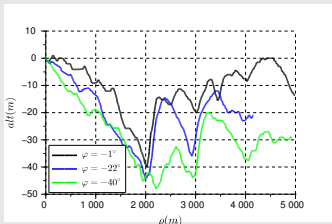
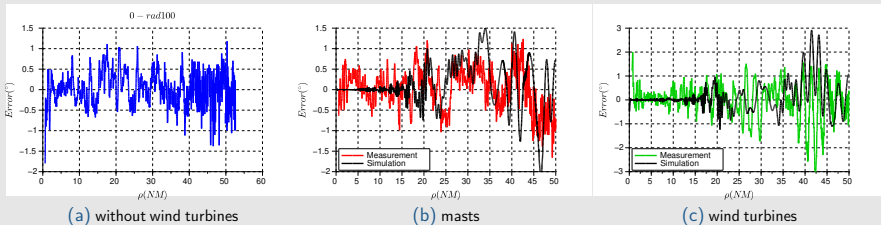


Figure 2: Relief from the VORC station to the wind turbines.

## Parameters

- Antenna of the Boulogne-sur-Mer VORC (113.8 MHz)
- 9 wind turbines on 3 radials
  - Mast : ground diameter = 7.5 m, top diameter = 2 m, height = 98 m
  - Nacelle : 4 m × 11 m × 4 m
  - Blades : length = 35.5 m
- Three in-flight campaigns:
  - Without wind turbines up to a distance of 15 km from the VOR (May 2009) ;
  - With wind turbines masts at approximately 5 km from the VOR (July 2012) ;
  - With complete wind turbines (November 2012).
- Ground with relief

# Simulated and measured VOR errors on radial $\varphi = -10^\circ$



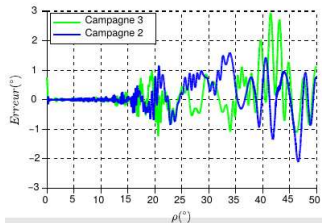
## Analysis

- Good agreement for the error envelop and maximal value
- Relatively strong residual error without wind turbines (other scatterers, noise)
- Rapid oscillations due to complex combination of multipath with various phases. Difficult to reproduce exactly in simulation

Computation time = 13 min

# Complementary analyses via simulations

## Influence of the aircraft trajectory



- **Configuration**

Two simulation campaigns with slight changes in the aircraft trajectories

- **Results**

Significant modification of the error  
⇒ Difficult to compare results for nearby trajectories



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# Statistical Description of the Configuration

## Objective

For one wind turbine of known approximate position and at a given observation point, determine the statistics of the multipath parameters ( $a_1, \theta_1, \phi_1$ )

## Statistical Parameters

- **Ground composition**

*Dry, wet, fresh water, sea water, ...*

⇒ Discrete uniform distribution

- **Windturbine position**

*Variation about the average position*

⇒ Normal distribution

- **Wind turbine characteristics**

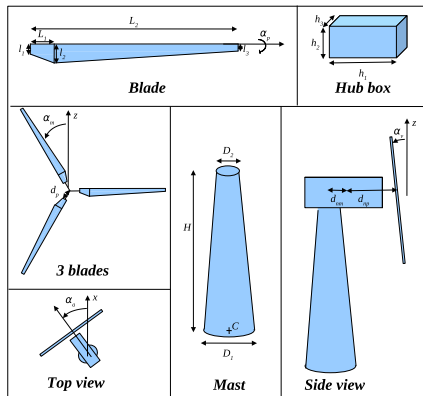
- 14 distances

*Mast length, hub box size, ...*

- 4 angles

*Blade orientation, rotor orientation, ...*

⇒ Uniform and normal distributions



# Probability Distribution for the Multipath Parameters

## Multipath Amplitude

- Statistical variations of the wind turbine characteristics
- Total wind Turbine scattering: Sum of the Scattering of the wind turbine components

Central limit theorem  $\Rightarrow$  Multipath amplitude follows a Rayleigh distribution

## Multipath Azimuth

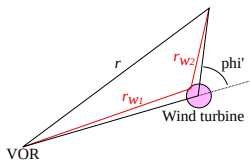
- Wind turbine position: normal distribution of standard deviation  $\sigma_w$
- $\sigma_w \ll$  distance VOR wind turbine

Azimuth of the multipath = Azimuth of the average position of the wind turbine

# Probability Distribution for the Multipath Parameters

## Configuration

- Wind turbine position: normal distribution of standard deviation  $\sigma_w$
- $r$  distance from VOR to aircraft
- $r_{w1}, r_{w2}$  distances from VOR to windturbine and from windturbine to aircraft
- Hypothesis  $\sigma_w \ll r_{w1}, r_{w2}$



## Distribution for the path length

Multipath length with respect to the direct path

$$d = r_{w1} + r_{w2} - r$$

Taylor series for  $\sigma_w \ll r_{w1}, r_{w2} \Rightarrow d$  follows a normal distribution of std

$$\sigma_d = 2 \sin\left(\frac{|\phi'|}{2}\right) \sigma_w$$

with  $\phi'$  angle between

- the VOR - Wind turbine axis
- the Wind turbine - Aircraft axis

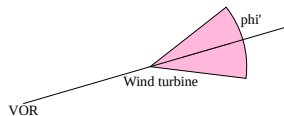
# Probability Distribution for the Multipath Parameters

## Distribution for the phase

- Relative phase of the multipath  $\arg e^{jkd}$ , with  $d$  normal distribution
- For  $\sigma_d \geq \lambda/2$ , almost uniform phase on  $0, 2\pi$

## Domain of uniform phase

- Uniform phase except for  $|\phi'| \leq 2 \arcsin \left( \frac{\lambda}{4\sigma_w} \right)$
- When  $\phi' \rightarrow 0$ , the error is null from Odunaiya expression



- For  $\sigma_w$  of few  $\lambda$ , uniform phase except in a region where the bearing error is weak
- *Example: For  $\sigma_w = 4\lambda \approx 10$  m, Uniform phase except for  $|\phi'| \leq 7^\circ$*

## Conclusion

- Rayleigh relative amplitude
- Constant azimuth
- Uniform relative phase

Need for only one parameter to characterize the multipath  
 $\Rightarrow$  The parameter of the Rayleigh distribution

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# Statistics of the bearing error

## One wind turbine

General Odunaiya expression

$$\varepsilon^C = \tan^{-1} \left( \frac{\sum_{n=1}^N a_n \cos(\theta_n - \theta_0) \sin(\varphi_n - \varphi_0)}{a_0 + \sum_{n=1}^N a_n \cos(\theta_n - \theta_0) \cos(\varphi_n - \varphi_0)} \right)$$

Expression for one weak multipath

$$\varepsilon^C = \frac{a_1}{a_0} \cos(\theta_1 - \theta_0) \sin(\phi_1 - \phi_0)$$

- $a_1/a_0$  Rayleigh distribution of parameter  $\sigma$
- $\theta_1 - \theta_0$  uniform distribution on  $0, 2\pi$

**Conclusion**  $\varepsilon^C$  centered normal distribution of standard deviation

$$\sigma_\varepsilon = \sigma |\sin(\phi_1 - \phi_0)|$$

## Several wind turbines

- Independant distributions for the multipath of each wind turbine

**Conclusion**  $\varepsilon^C$  centered normal distribution of standard deviation

$$\sigma_\varepsilon = \sqrt{\sum_{n=1}^N \sigma_n^2 \sin^2(\phi_1 - \phi_0)}$$

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# Test-Case

## Configuration

### Deterministic parameters

- VOR Station of power 50 W and frequency 113 MHz
- Aircraft position : Half sphere of radius 10 km centered on the Wind Turbine
- Windturbine at 3 km from the VOR, on radial  $90^\circ$

### Statistical parameters

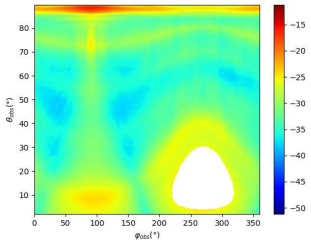
- Wind turbine characteristics: database of 2000 wind turbines installed in the North of France

## Monte Carlo simulations

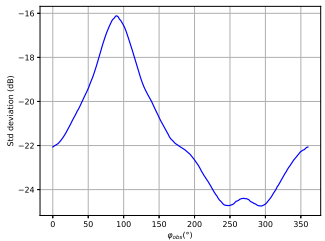
- Objective: assess the parameter of the Rayleigh distribution
- VERSO is run for several samples of the input parameters
- Convergence test: estimated value variations weaker than 5% during the 10 last iterations

# Rayleigh parameter

## Results



**Complete half-sphere**



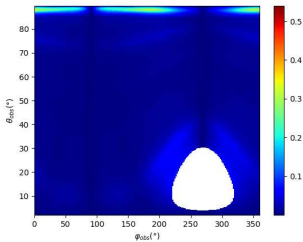
**For  $\theta = 88^\circ$**

## Comments

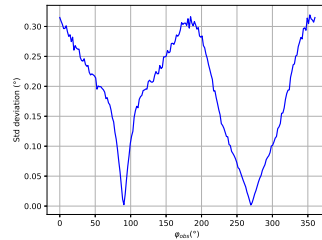
- Low Elevation: strong multipath due to the mast
- Medium elevation: residual contribution due to the blades
- Near zenith: spurious increase of the relative multipath in the blind cone

# Bearing Error

## Results



Complete half-sphere



For  $\theta = 88^{\circ}$

## Comments

- Low Elevation: strong multipath due to the mast
- Medium elevation: residual contribution due to the blades
- Near zenith: spurious increase of the relative multipath in the blind cone

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# Conclusion

## Conclusion

### Multipath Probability Distribution

For a wind turbine of known approximated position and at a given observation point, the multipath is so that

- Uniform relative phase
- Constant relative azimuth
- Rayleigh relative amplitude

Parameter of the Rayleigh distribution via Monte Carlo Simulation

### Bearing error Probability Distribution

- For one wind turbine, centered normal distribution
- For several wind turbines, centered normal distribution if multipath are independant

## Future works

- Develop a method to avoid to run one MC simulation per wind turbine and per aircraft positions  
⇒ Huge computation resources
- Include the terrain relief
- Similar work for Doppler VOR