# Electromagnetic Modelling of Time-Variant Propagation Effects due to Rotating Wind Turbines

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**Frank Weinmann**,
Josef G. Worms, Peter Knott

Antenna Technology and
Electromagnetic Modelling

Fraunhofer Institute for High-Frequency Physics
and Radar Techniques (FHR)

Wachtberg, GERMANY

frank.weinmann@fhr.fraunhofer.de



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# Overview

- Background: Influence of Wind Turbines on Operation of Air Surveillance Radar Systems
- Introduction: Measurement Campaigns
  - Ground Measurements
  - Commercial Hexacopter
- Electromagnetic Simulations of Wind Farm Scenarios
  - Ray Tracing Approach
  - Setup of Scenarios
  - Typical Results (Frequency Domain)
- Evaluation of Simulation Data in Time Domain
- Summary and Conclusions

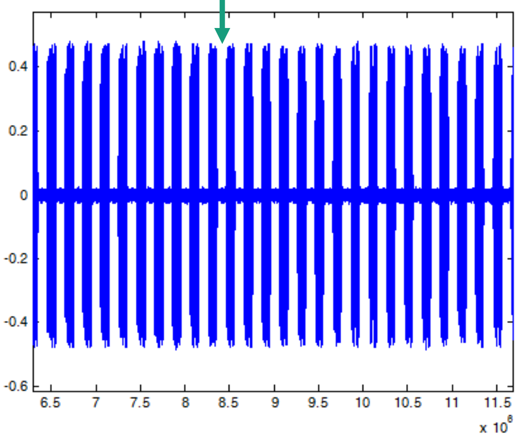
# Measurement Equipment

Ground measurements


FHR experimental airplane „Delphin“

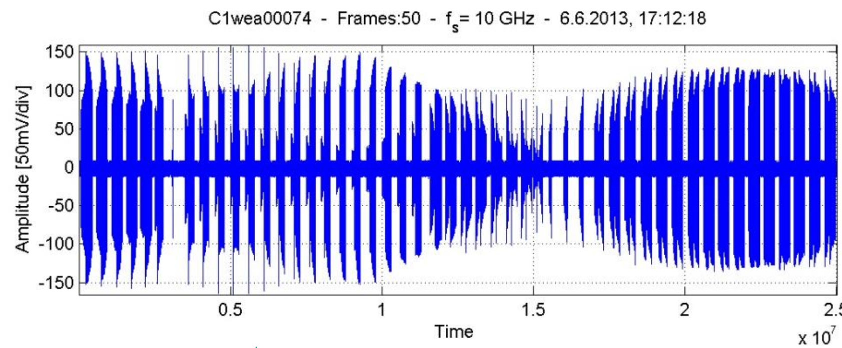
# Typical Measurement Results

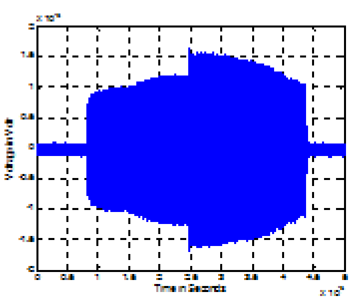
Without WEA in propagation path:
- Typical pulse series obtained

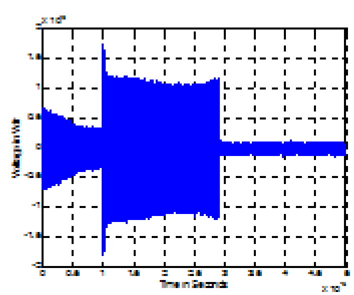


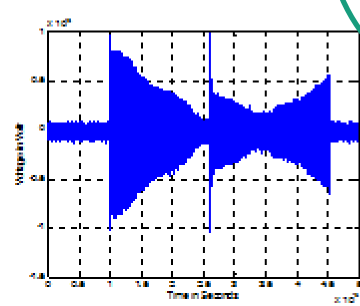

## Typical Observations behind WEAs:

- Fluctuations of pulse power over time
- Change of pulse modulation caused by WEA
- Effects observed in different measurements







With WEA in propagation path:
- Typical pulse series
- Typical pulse modulations



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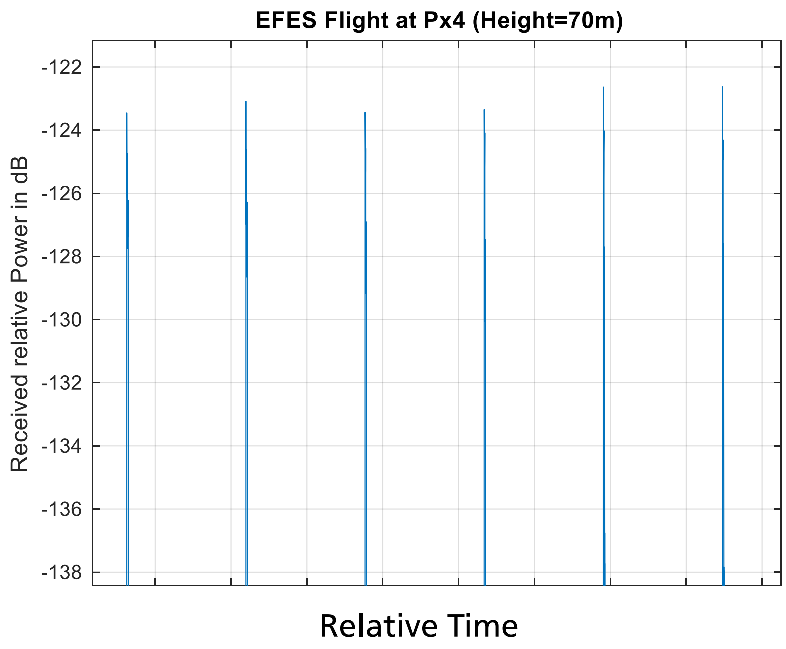
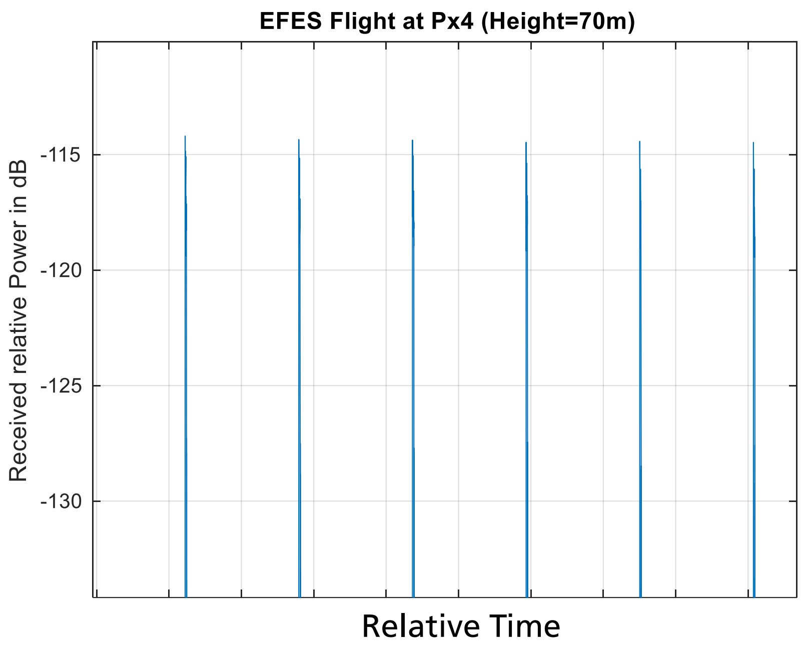
# Measurements Using a Hexacopter

## Measurement Platform:

- Commercially available hexacopter
- Control unit and receiver system designed for the measurements
- Field strengths at several locations have been recorded at different heights (max. 100 m)
- Antenna turned towards the air surveillance radar automatically
- Constant position during recording of field strength data
- Each data set covers a time frame including several pulses transmitted by the radar (corresponding to a very short cut through the simulated data)

# Measurement Results (1)




## Results at 70m height:

- Same height but during two different measurement sequences (corresponding to different rotation angles)
- Relative difference of 8 dB
- Good agreement of field strength variation with simulated data



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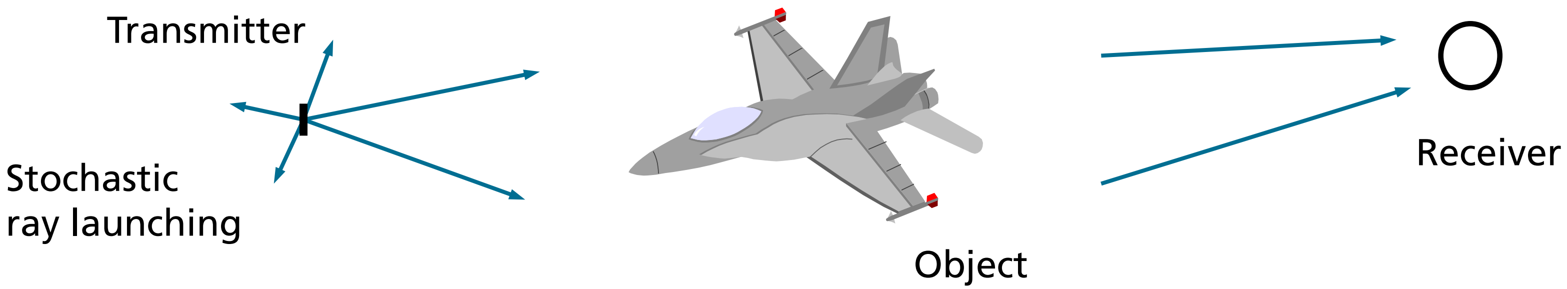
# Simulation Approach
# EM Fields Calculation with SBR Ray Tracing




## Ray Tracing Method:

*(Geometrical Calculation of Propagation Paths)*

Shooting-and-Bouncing Rays (SBR), number of reflections practically unlimited

Discrete rays as representatives of ray tubes

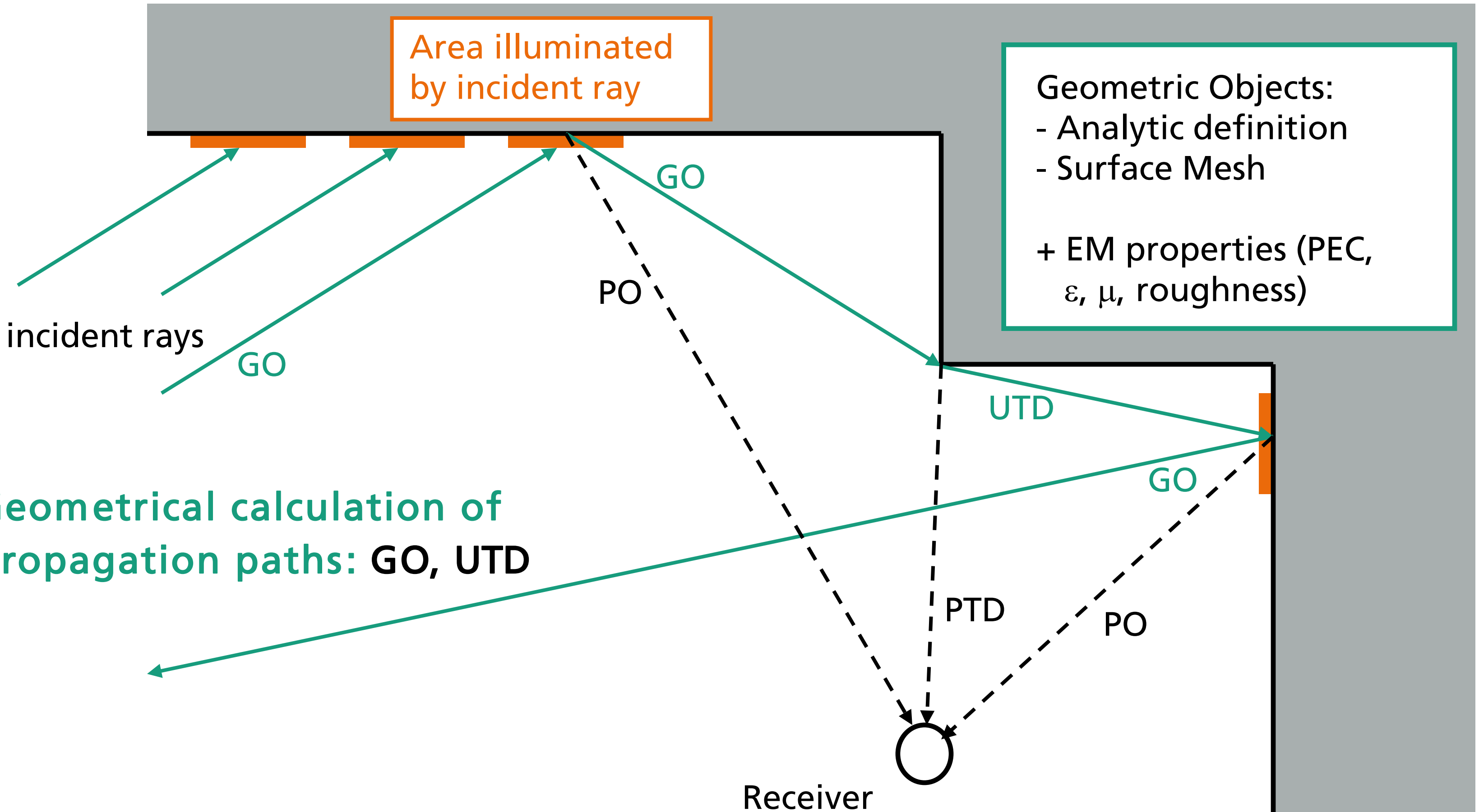
Ray-Density Normalisation (RDN) states the “distance” between rays

## Calculation of Field Strength Contributions to Receiver:

*(each time a ray hits the object)*

Physical Optics (PO) + Physical Theory of Diffraction (PTD)

# Ray Tracing: Combination of GO/UTD-PO/PTD




**Geometrical calculation of propagation paths: GO, UTD**

**Calculation of field contributions:**

(each time a ray hits the object) **PO, PTD**

GO and PO also implemented for dielectric objects



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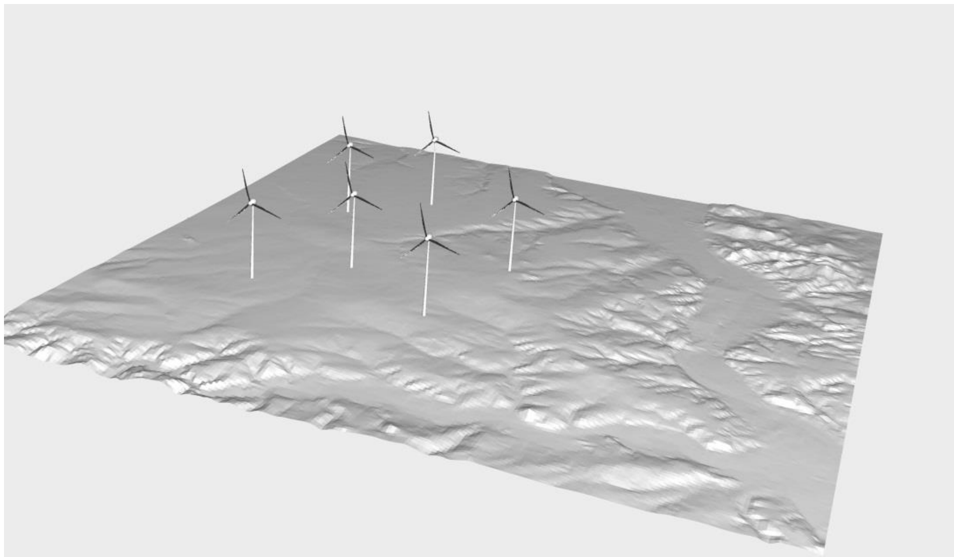
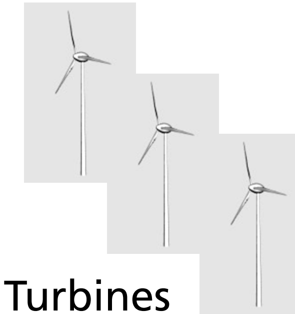
# Schematic Setup of Simulations





Wind Turbines
(CAD-Model in NASTRAN format)

Transmitter Specification
(Location, main lobe direction)

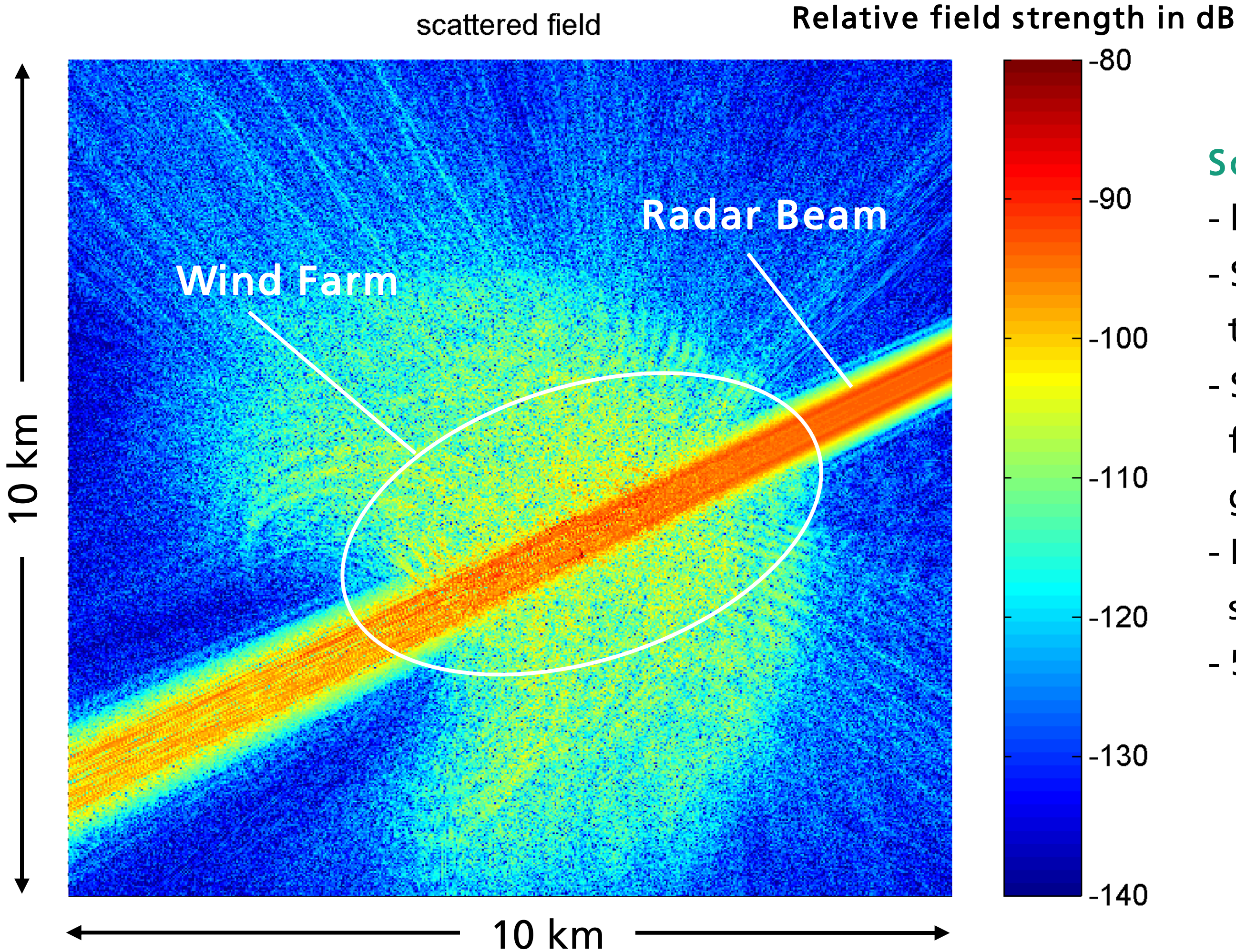
Receiver Specification
(Single point, 1D, 2D arrays,...)

Terrain (CAD-Model in NASTRAN format)

**Ray Tracing Simulation**

Output / Postprocessing:
Field Strengths
(Single point, 1D, 2D arrays,...)

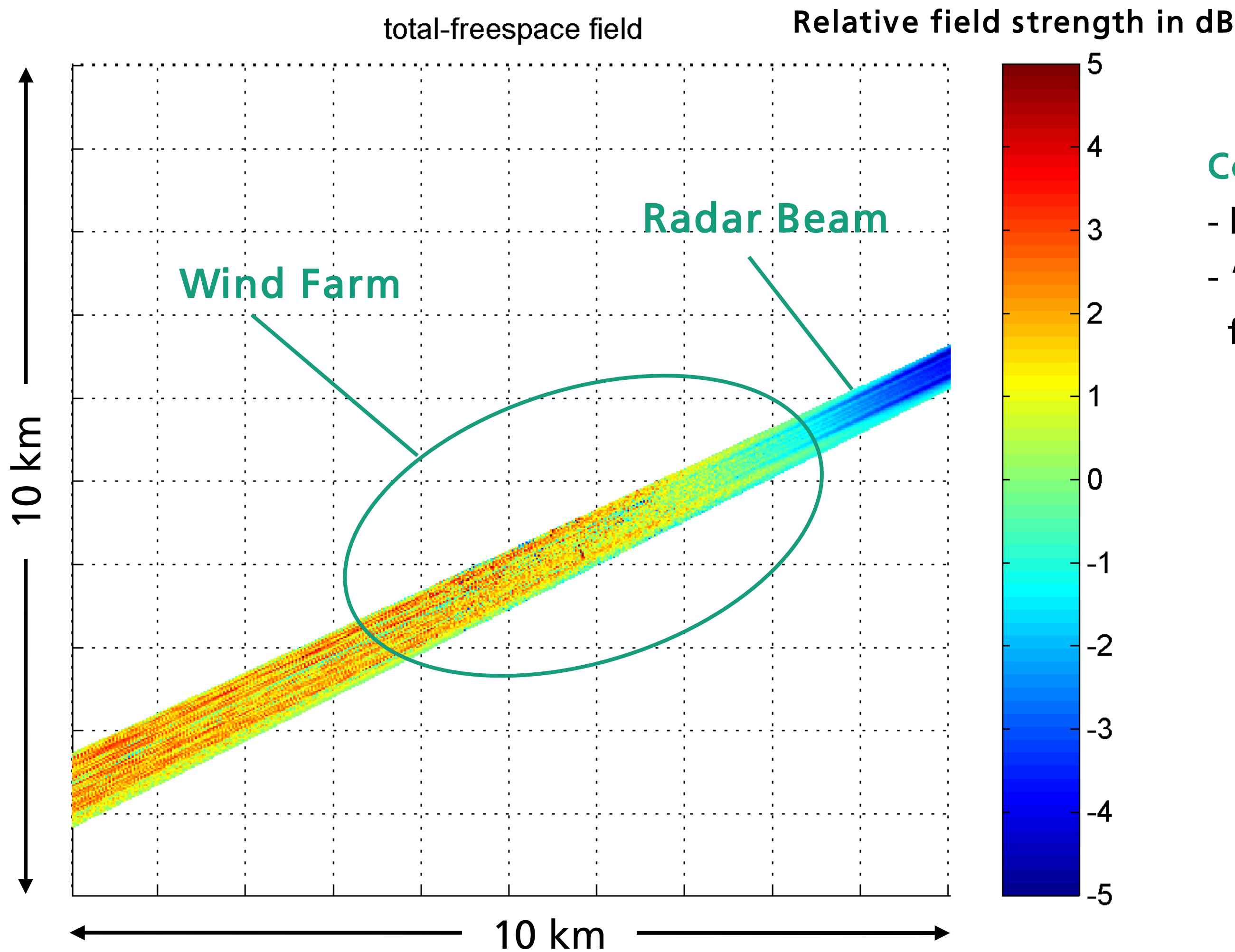
# Wind Farm, Static Scenario (2D Field Distribution)




**Scattered Fields**

- h = 100 m
- Scattering from wind turbines
- Scattering (i.e. reflection) from dielectric smooth ground
- Results include multiple scattering
- 501x501 observation points!

# Simulation Results for Wind Farm (2D Field Distribution)




**Comparison to Free Space**

- h = 100 m
- “Free Space”: Theoretical field strengths in free space



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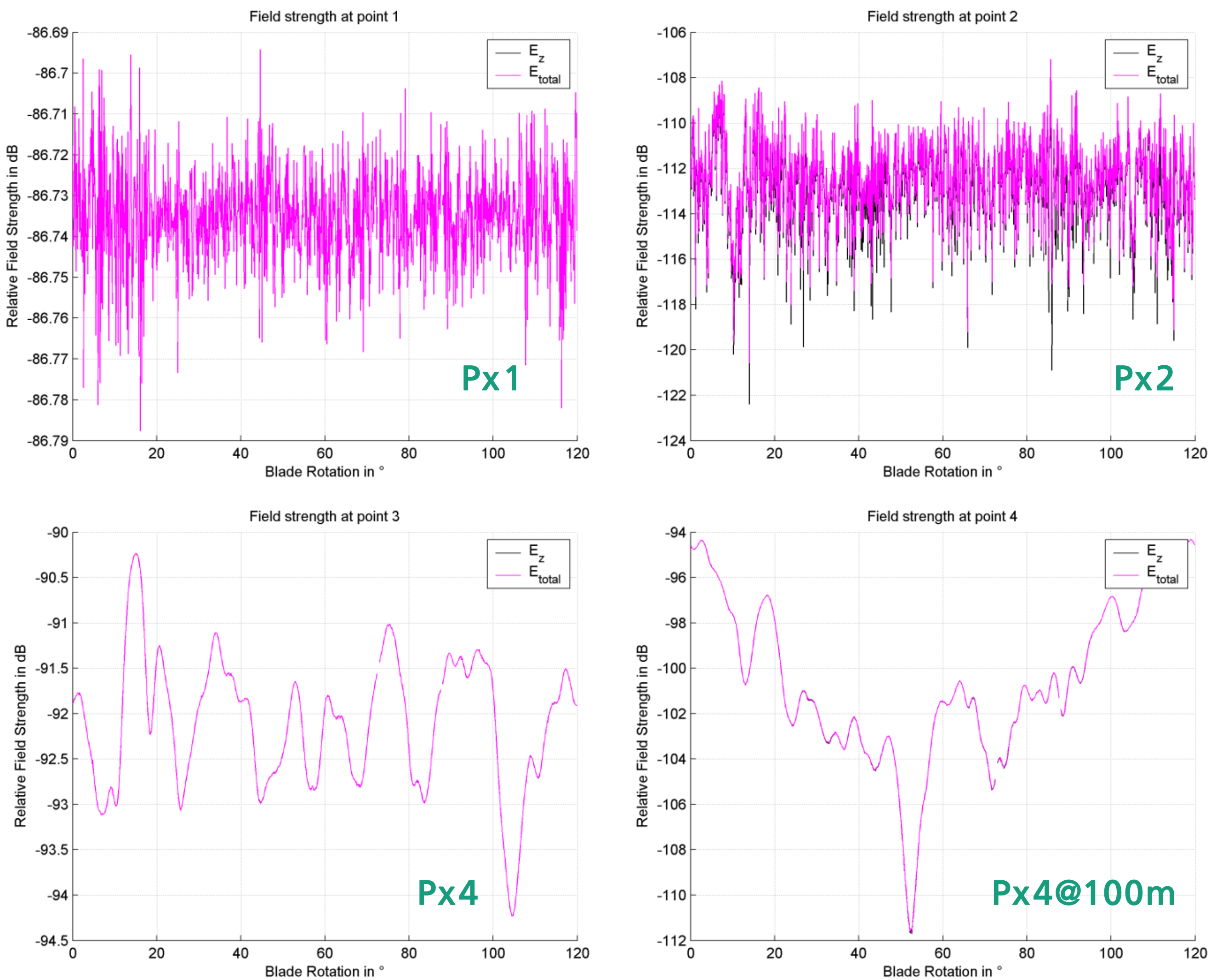
# Wind Farm, Rotating Blades




## Simulation Setup:

- Fixed observation points; sequence of quasi-static scenarios

## Observation:

- Simulation data show variation of field strengths, similar behavior as in measurements
- Variation of field strength also for distant (50km, 100km) observation points



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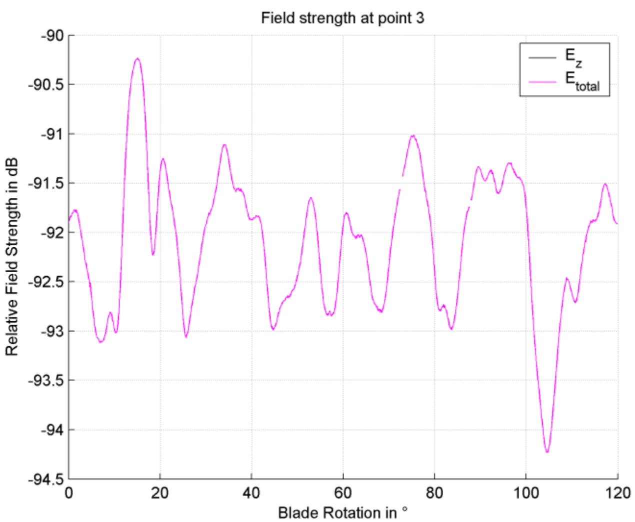
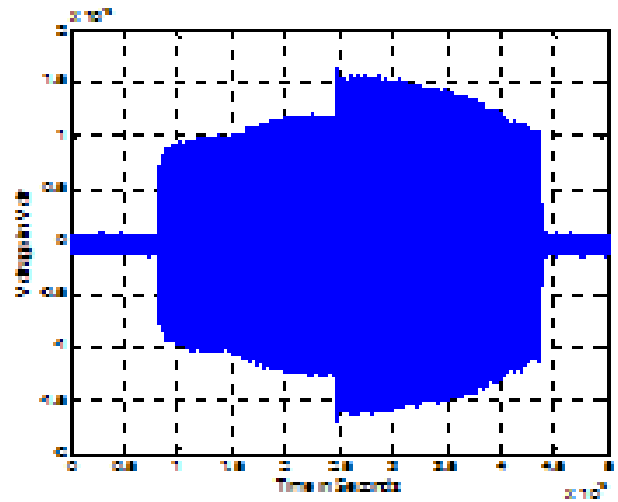
# How to Compare Simulated and Measured Data



**Simulated Data:**

- Approach 1: Sequence of data in frequency domain

**Measured Data:**

- Pulse modulation in time domain

Results not exactly comparable



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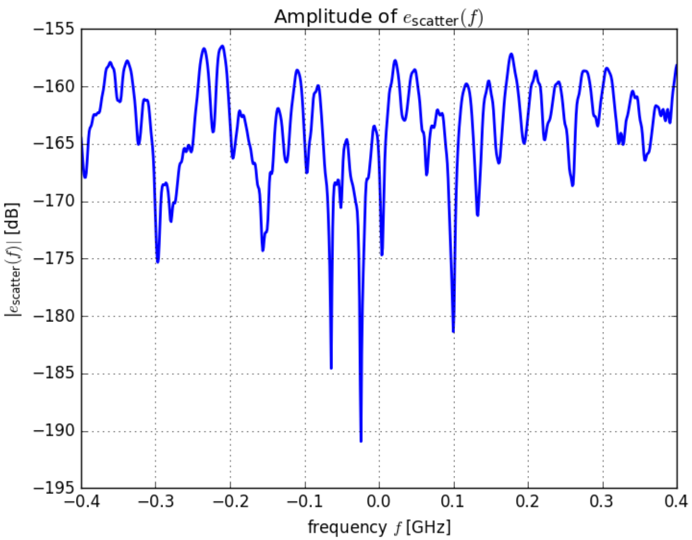
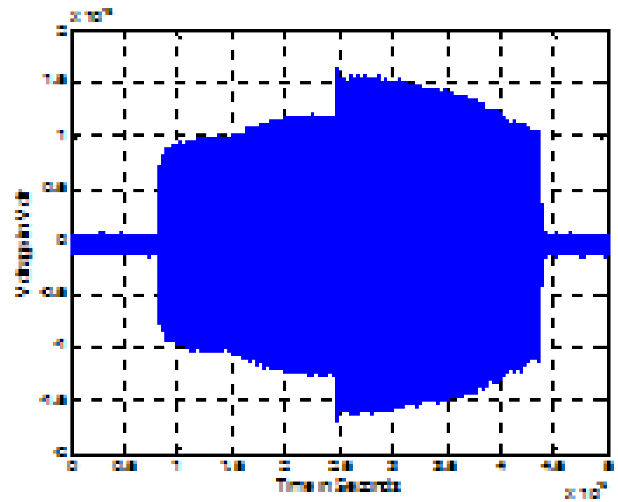
# How to Compare Simulated and Measured Data



## Simulated Data:

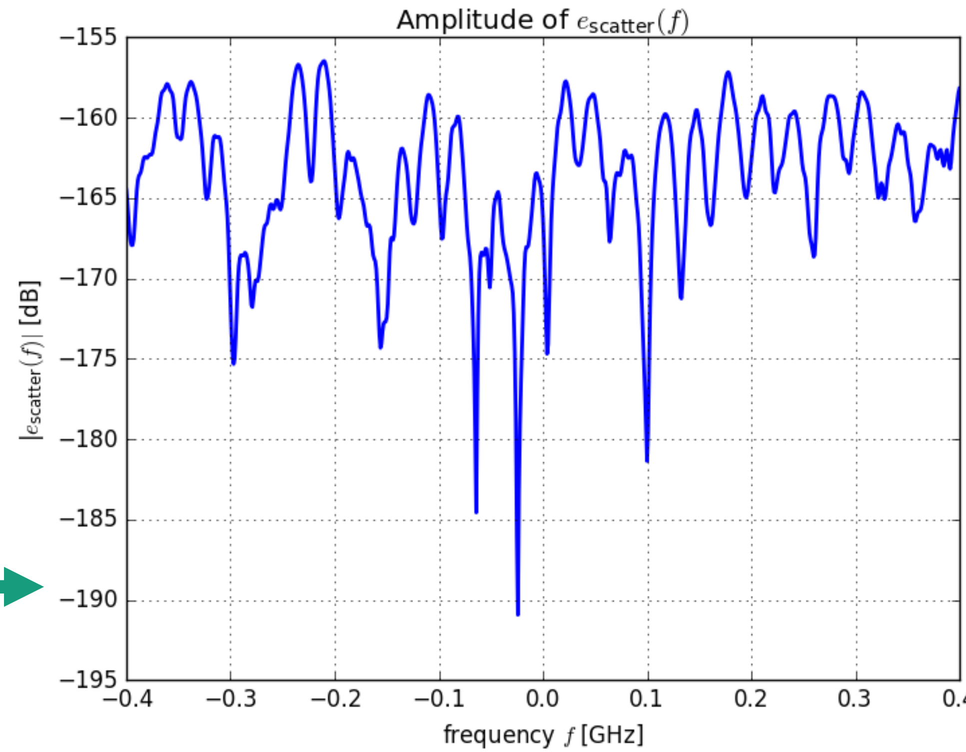
- Approach 2: *N* frequency data points
- Bandwidth: (*N*-1) $\Delta f$
- covered time window: T = (*N*-1) $\Delta t$, should be large enough to contain the scattered pulse, which leads to a minimum number of frequency data points

## Measured Data:

- Pulse modulation in time domain

# Simulation of Scattered Fields in Frequency Domain

Ray Tracing Simulation




## Simulation Data:

- Frequency Domain Method (GO+PO)
- Can be provided for a given bandwidth
- $e_{scatter}(f)$ is significantly frequency-dependent, as one would expect due to the superposition of scattering contributions from an electrically large structure

$$e_{scatter,sim}(f) = \frac{E_{scatter,sim}(f)}{E_{init,sim}}$$



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# Representation of Pulse Forms in Time Domain

## Arbitrary Electromagnetic Pulse

can be described as real part of:

$$\boldsymbol{E}(t) = [\boldsymbol{e}_{\mathrm{v}} A_{\mathrm{v}}(t) + \boldsymbol{e}_{\mathrm{h}} A_{\mathrm{h}}(t)] e^{j2\pi f_0 t}$$

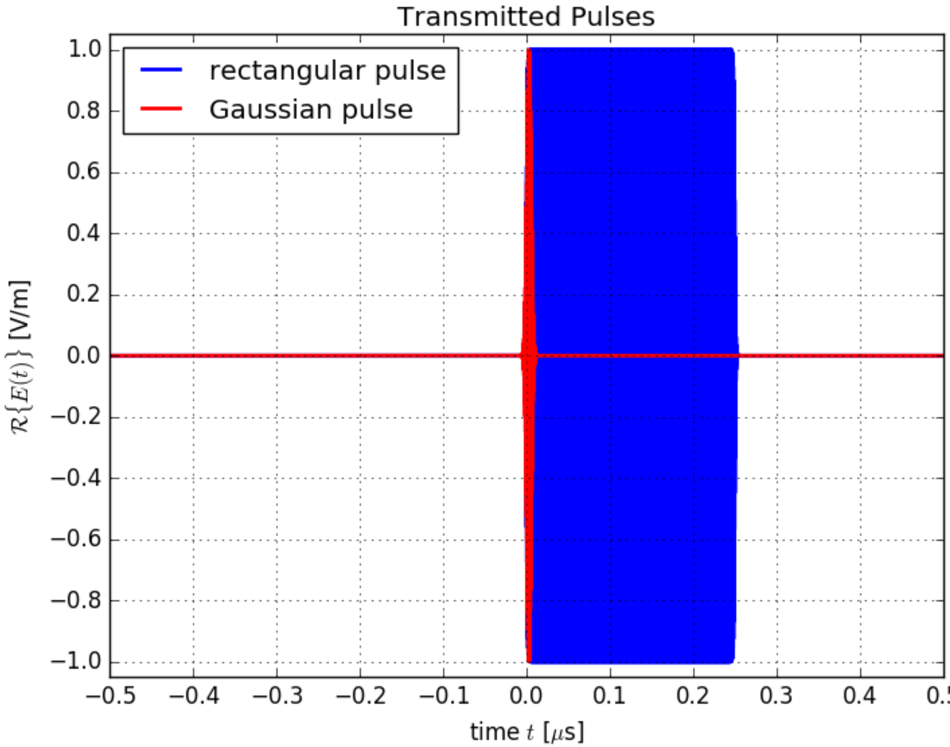
$A_{\mathrm{i}}(t)$ [V/m] is the complex, time dependent envelope of the pulse

## Gaussian Pulse:

$$A_{\mathrm{gauss}}(t) = A_0 e^{-\frac{\left(t - t_{\mathrm{pulse}}\right)^2}{2\sigma_{\mathrm{gauss}}^2}}$$

## Smoothed Rectangular Pulse:

$$A_{\mathrm{rect}}(t) = A_0 \left\{ \frac{1}{2}\left[1 + \tanh\left(\frac{t - t_{\mathrm{rise}}}{T_{\mathrm{rise}}}\right)\right] - \frac{1}{2}\left[1 + \tanh\left(\frac{t - t_{\mathrm{fall}}}{T_{\mathrm{fall}}}\right)\right] \right\}$$



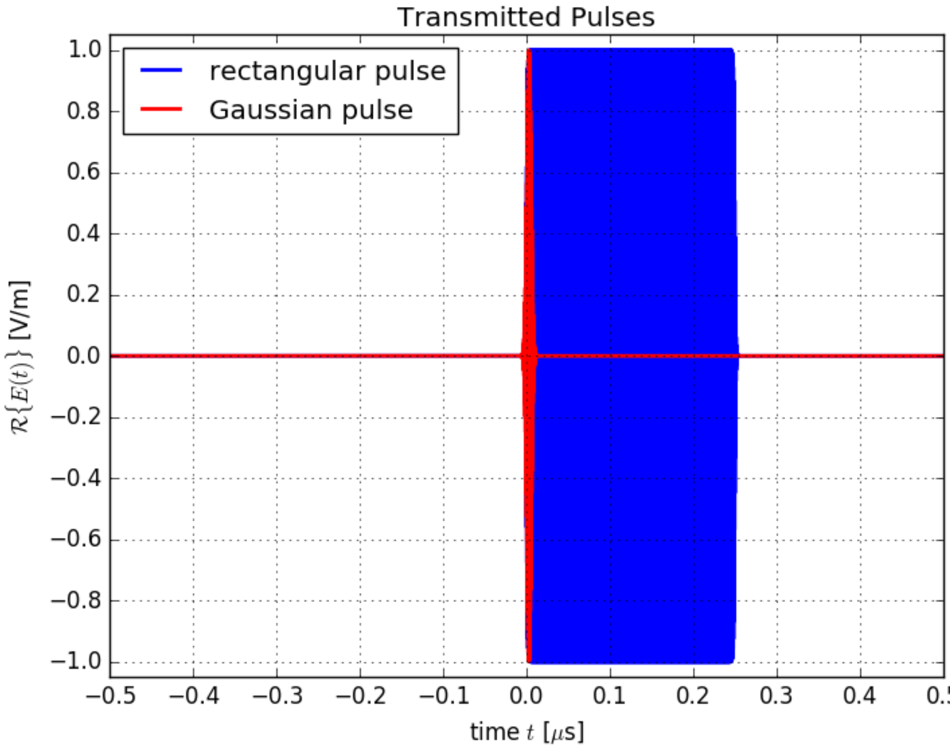
# Representation of Pulse Forms in Time Domain

**Gaussian Pulse:**

$$A_{\text{gauss}}(t) = A_0 e^{-\frac{\left(t-t_{\text{pulse}}\right)^2}{2\sigma_{\text{gauss}}^2}}$$

**Smoothed Rectangular Pulse:**

$$A_{\text{rect}}(t) = A_0 \left\{\frac{1}{2}\left[1 + \tanh\left(\frac{t-t_{\text{rise}}}{T_{\text{rise}}}\right)\right] - \frac{1}{2}\left[1 + \tanh\left(\frac{t-t_{\text{fall}}}{T_{\text{fall}}}\right)\right]\right\}$$




**Arbitrary choice of parameters (to showcase pertinent effects):**

$T_{rise}$ = 1.25 µs, pulse duration: 2.5 ns (Gauss pulse), 0.25 µs (rectangular pulse)

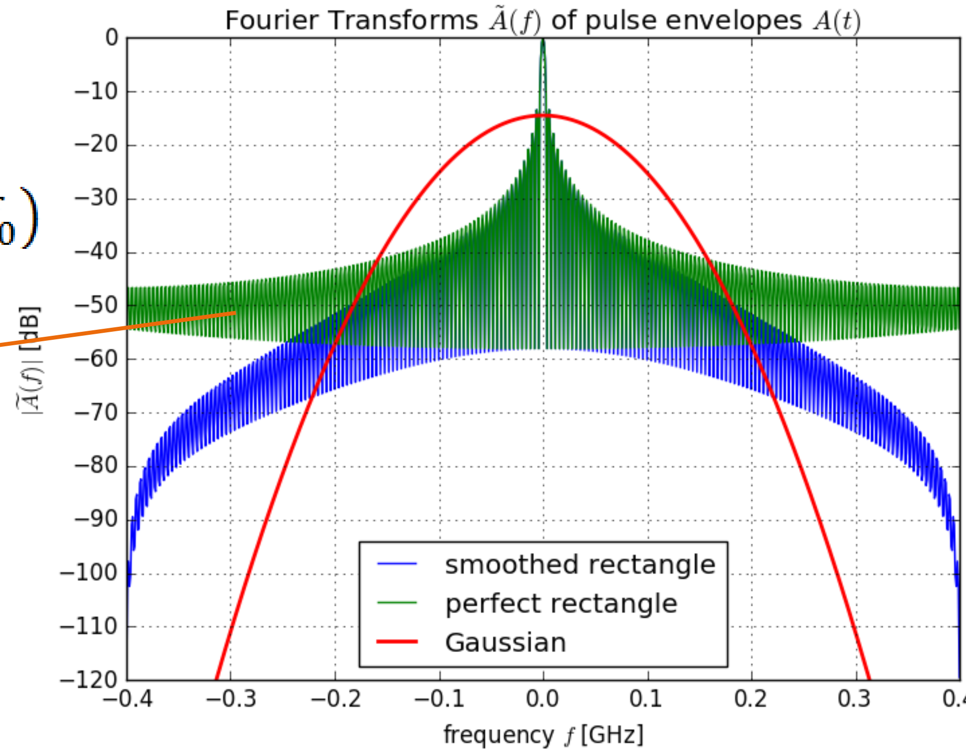
Bandwidth 0.8 GHz, $\Delta f$ = 1 MHz, $T$ = 1 µs

# Transformation of Pulses to Frequency Domain

## Fourier Transform of Electric Field:

$$F\{E(t)\} = \tilde{A}(f) * \delta(f - f_0) = \tilde{A}(f - f_0)$$

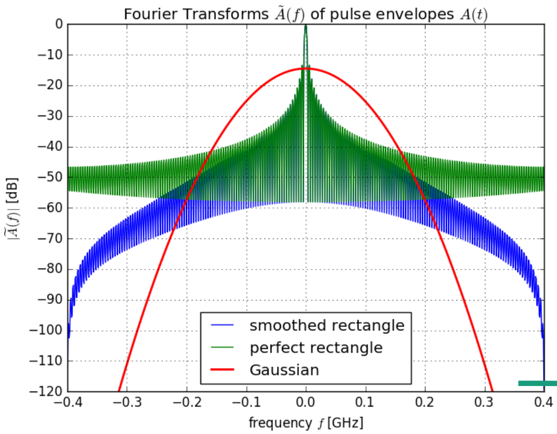
Perfect rectangular pulse for comparison

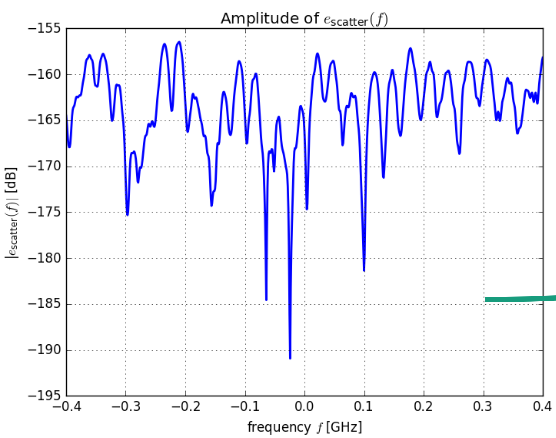



## After Fourier Transformation:

- Cut spectrum according to bandwidth of simulated data
- Might lead to inaccuracy if pulse has significant contributions out of simulated band

# Transformation back to Time Domain (1)




In frequency domain, the Fourier Transform of the pulse envelope is multiplied with the down-converted scattering results from the ray tracing simulation

## Scattered Pulse in Time Domain:

$$E_{\text{scatter}}(t) = \mathrm{F}^{-1}\{e_{\text{scatter,sim}}(f + f_0)\widetilde{\mathrm{A}}(f) * \delta(f - f_0)\}$$
$$= \mathrm{F}^{-1}\{e_{\text{scatter,sim}}(f + f_0)\widetilde{\mathrm{A}}(f)\}\mathrm{e}^{\mathrm{j}2\pi f_0 t}$$



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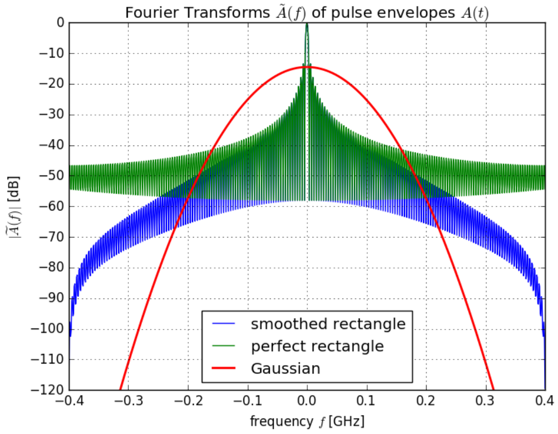
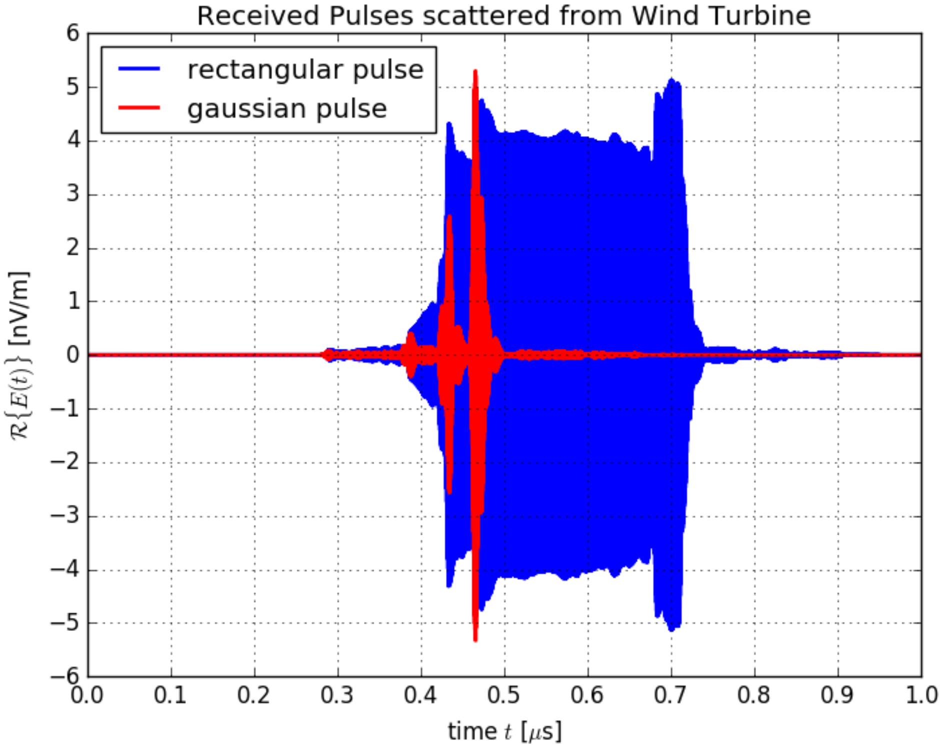
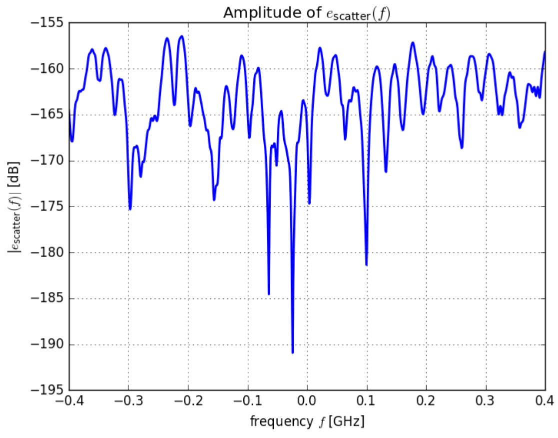
# Transformation back to Time Domain (2)

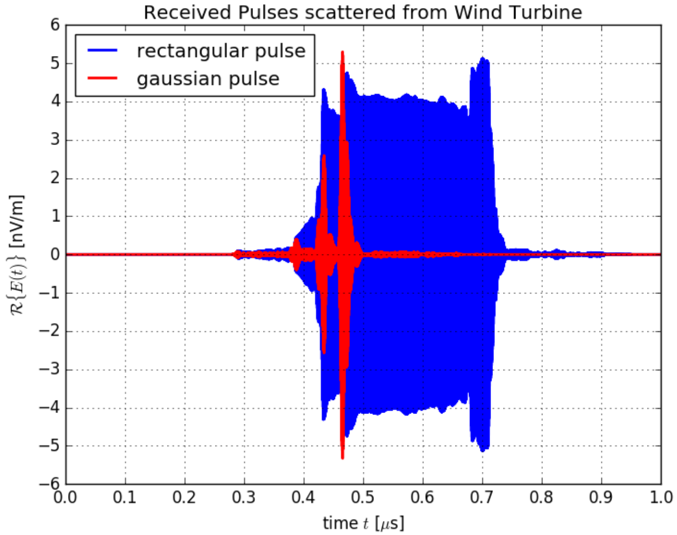


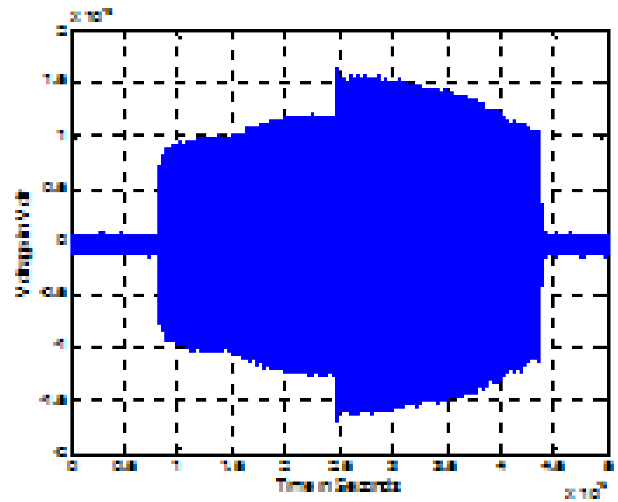

## Scattered Pulse in Time Domain:



# How to Compare Simulated and Measured Data (2)




## Simulated Data:

- Scattered pulse in time domain
- Time domain post-processing can be done for arbitrary pulses without the need of repeating the simulation for each pulse

## Measured Data:

- Pulse modulation in time domain

# Summary

- Measurements:
  Fluctuations in the order of several dB are to be expected for the electromagnetic fields behind wind farms
- EM Simulations:
  Frequency Domain Simulations; Studies of Time Variance: Good qualitative agreement with measurements
- Modelling of Scattered Pulses in Time Domain
  Broadband frequency domain simulation of scattered fields
  Multiplication with Fourier Transform of pulse
  Transformation back to time domain
  Time domain post-processing for arbitrary pulses

# Literature


- F. Weinmann, J. G. Worms, P. Knott, "The Influence of Time-Variant Propagation Effects due to Rotating Wind Turbines," 2017 European Radar Conference (EuRAD), 9-13 October 2017, Nuremberg, Germany.
- F. Weinmann, "EM Modelling of Radar Signatures of Targets Behind Wind Farms – A Time-Gating Ray Tracing Approach," 2016 European Radar Conference (EuRAD), 3-7 October 2016, London, UK.
- F. Weinmann, J. G. Worms, "EM Scattering Effects Caused by Wind Turbines," EuCAP 2016 10th European Conference on Antennas and Propagation, 10-14 April 2016, Davos, Switzerland.
- F. Weinmann, J. G. Worms, "Time-Variant Scattering Properties of Wind Turbines," EuCAP 2015 9th European Conference on Antennas and Propagation, 13-17 April 2015, Lisbon, Portugal.
- F. Weinmann, "High-Frequency Electromagnetic Simulation of Wind Turbines in Realistic Scenarios and Approximation Techniques for Reducing the Complexity of Computations," 9th Future Security 2014, 16-18 September 2014, Berlin, Germany.
- F. Weinmann, "Accurate Prediction of EM Scattering by Wind Turbines," EuCAP 2014 8th European Conference on Antennas and Propagation, 6-11 April 2014, The Hague, The Netherlands.