Analysis and simulation of micro-Doppler features of wind turbine's clutter: recent progress in extensions of TU Delft's simplified model

Oleg A. Krasnov,

S. Medagli, K. Wangkheimayum and Alexander G. Yarovoy

Microwave Sensing, Systems and Signals (MS3)
Delft University of Technology, The Netherlands

O.A.Krasnov@tudelft.nl

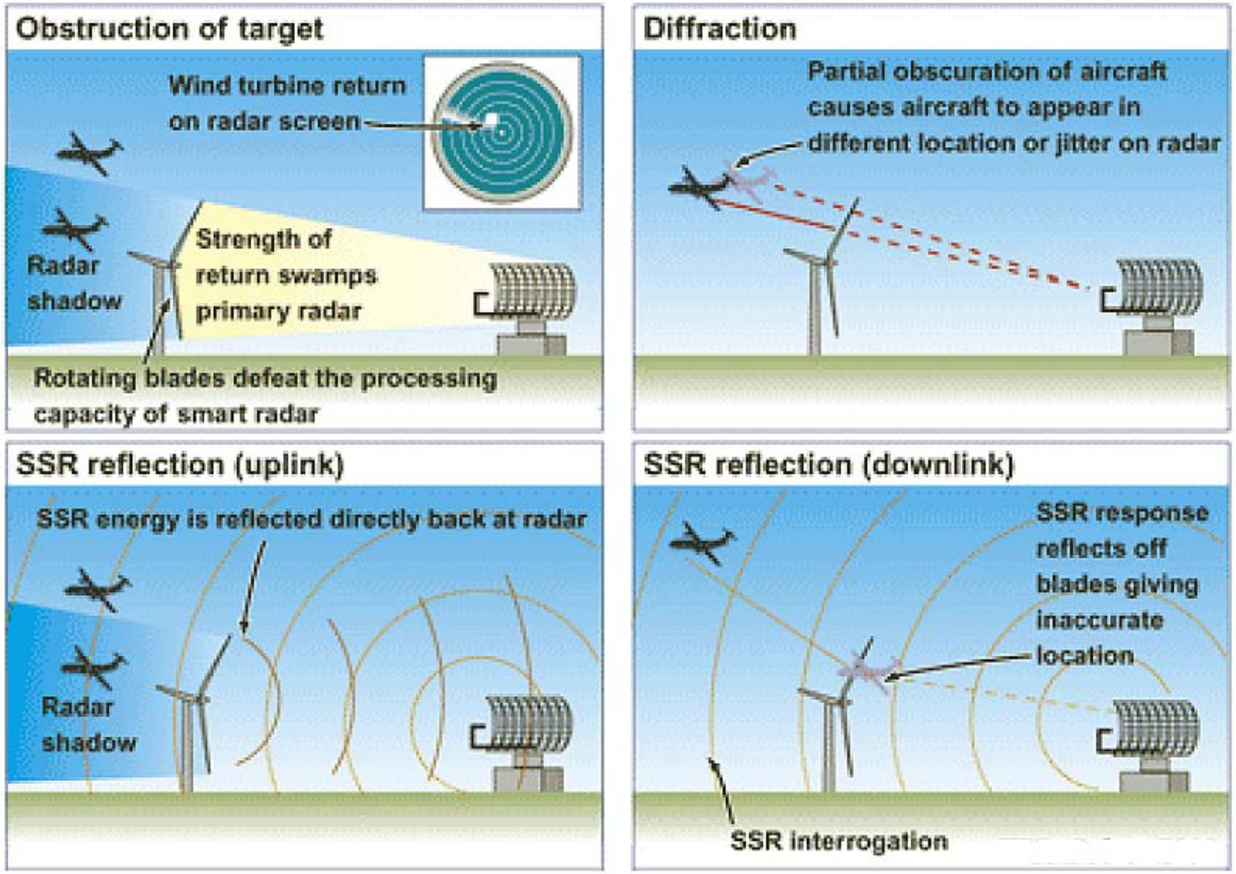
Contents and Schedule

- Introduction into the problem
- EM Model of rotating linear wired construction
- Rotation Frequency and Doppler spectrum
- Model extensions
- Comparison with measurements
- Conclusions

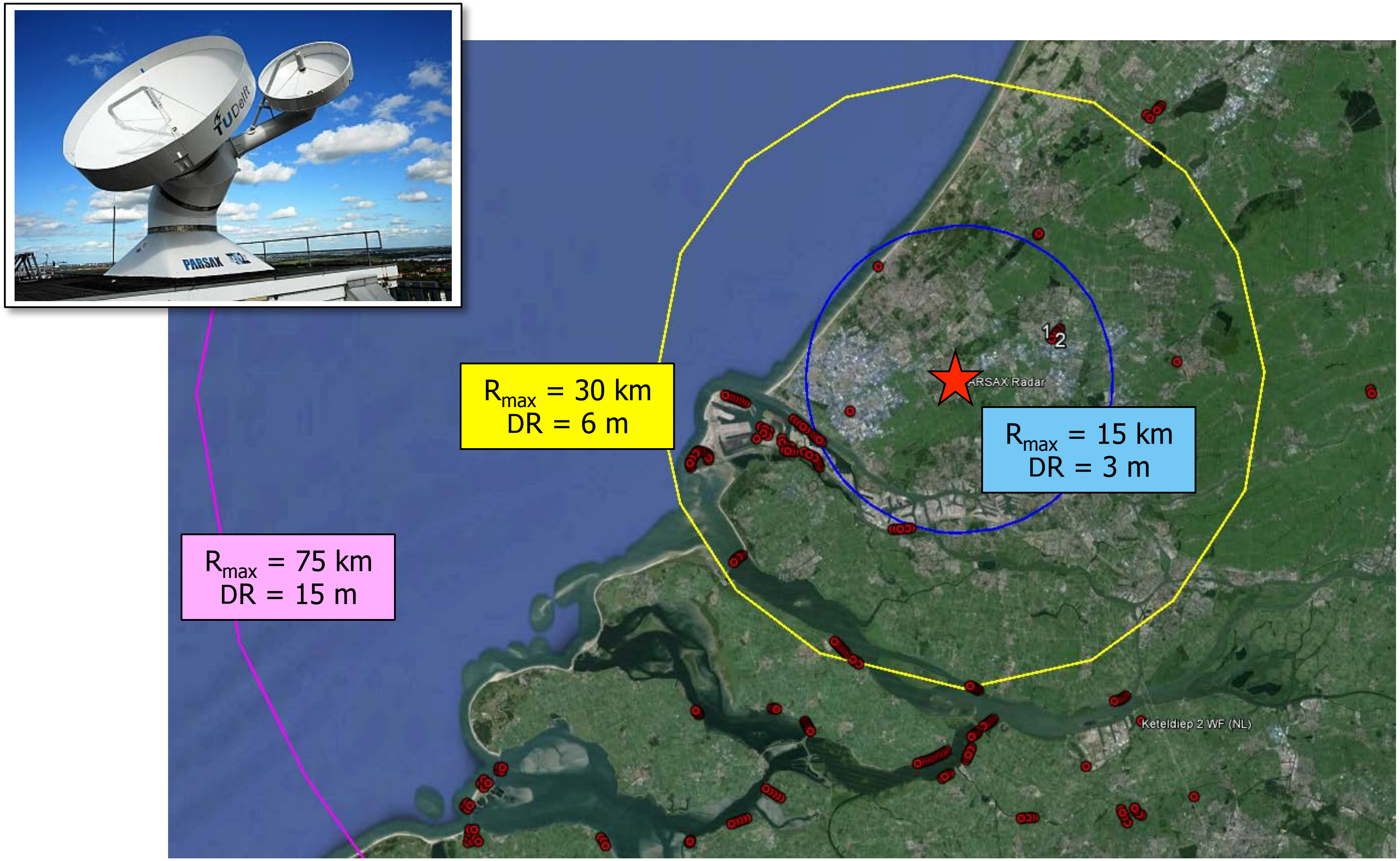
Wind-Turbines vs Radar

For surveillance and weather radars wind turbines may shadow targets and create heavy clutter that dynamically changes in time.

Time-variable diffraction of signals on WT's blades produces interferences to communication and navigation systems



The PARSAX – S-band polarimetric reconfigurable radar



Wind-Turbines vs Radar

Wind turbines at Zoeterwoude

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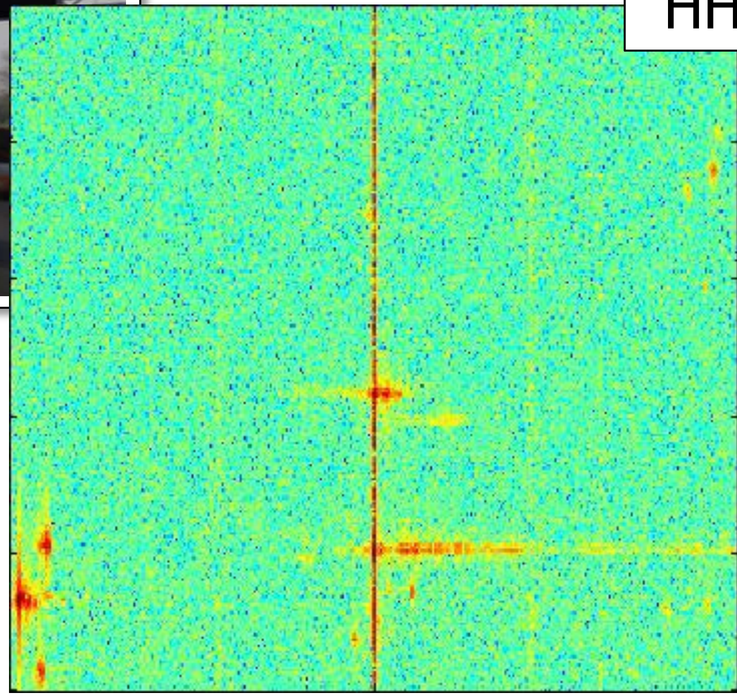
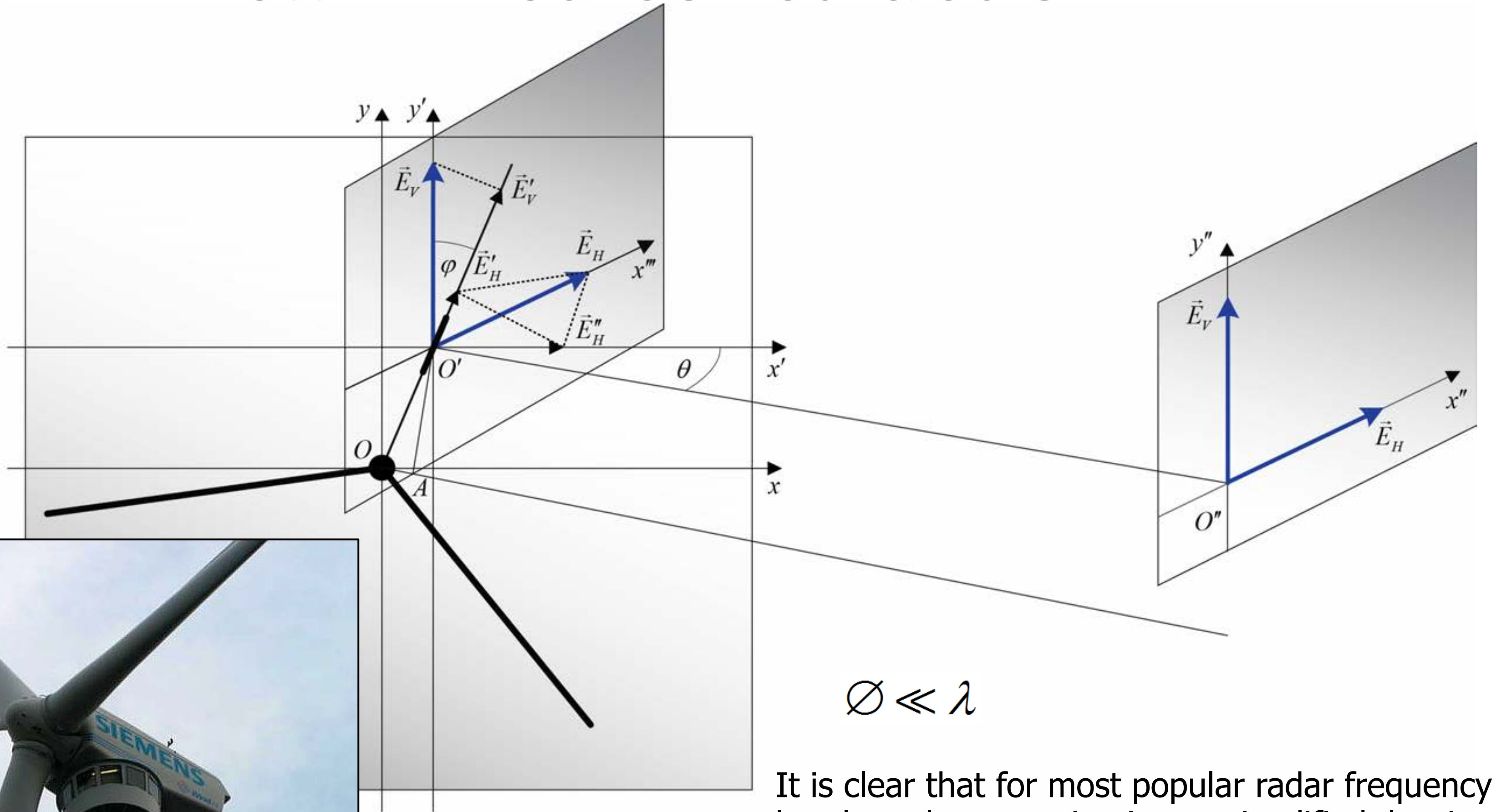


Range

Doppler frequency

Wind turbine model: finite length linear wired construction



$$\varnothing \ll \lambda$$

It is clear that for most popular radar frequency bands such suggestion is oversimplified, but it gives the possibility to obtain easy to analyze basic close form solutions of radar observables the far-field region.

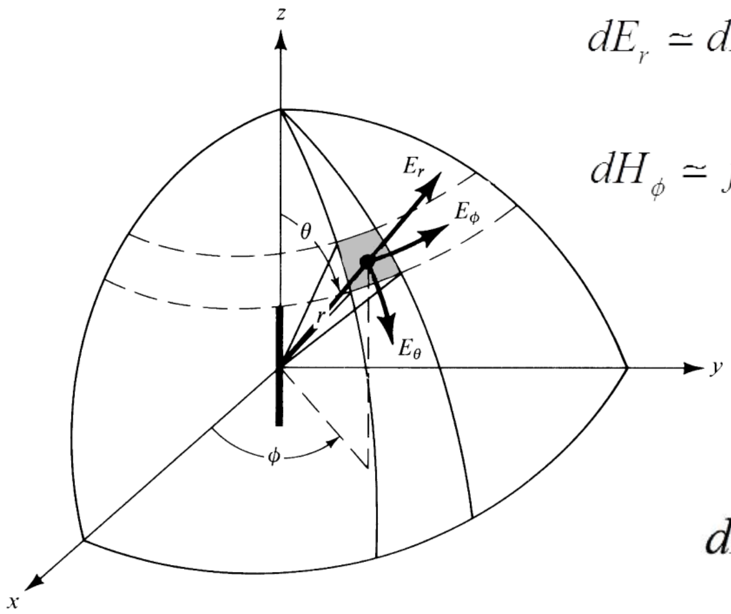
Basic relations for an infinitesimal dipole and finite wire

$$dE_\theta \simeq j\eta \frac{kI_e(x',y',z')e^{-jkR}}{4\pi R}\sin\theta dz'$$

$$dE_r \simeq dE_\phi = dH_r = dH_\theta = 0$$

$$R = \sqrt{r^2 + \left(-2rz'\cos\theta + z'^2\right)}$$

$$dH_\phi \simeq j \frac{kI_e(x',y',z')e^{-jkR}}{4\pi R}\sin\theta dz'$$



Using the far-field approximation, when

- $R \simeq r - z'\cos\theta$ for phase terms
- $R \simeq r$ for amplitude terms

$$dE_\theta = j\eta \frac{kI_e(x',y',z')e^{-jkr}}{4\pi r}\sin\theta e^{+jkz'\cos\theta}dz'$$

Radiated field of finite length linear wired structure

$$E_\theta = \int_L dE_\theta = j\eta \frac{ke^{-jkr}}{4\pi r}\sin\theta\left[\int_L I_e(x',y',z')e^{jkz'\cos\theta}dz'\right]$$

Constantine A. Balanis. *Antenna Theory: Analysis and Design*, 3rd Ed.- Wiley, 2005

Rotation and Doppler Spectrum

Radiated electric field, when radar is placed in the rotation plane

$$\theta(t) = \theta_0 + \Omega t \;,\; \Omega \ll \omega$$

$$E_\theta = \int_L dE_\theta = j\eta \underbrace{\frac{ke^{-jkr}}{4\pi r}\sin\theta}_{\text{Amplitude modulation}} \underbrace{\left[\int_L I_e(x',y',z')e^{jkz'\cos\theta}dz'\right]}_{\text{Phase modulation}}$$

Radar measure the Doppler characteristics of targets during finite intervals of time – observation time interval Δt .

What radar will observe in case of different relations between observation time and rotation period?

Slowly rotating objects

In this case the observation time is much shorter than rotation period

$$\Omega \Delta t \ll 1$$

Serial expansion

$$\cos\theta(t) = \cos(\theta_0 + x) = \cos\theta_0 - x\sin\theta_0 - \frac{x^2}{2!}\cos\theta_0 + \frac{x^3}{3!}\sin\theta_0 + \ldots$$

where $x = \Omega t$.

As result, keeping only linear member of the expansion,

$$e^{jkz'\cos\theta(t)} e^{j\omega t} \approx e^{jkz'\cos\theta_0} e^{j(\omega - \Omega kz'\sin\theta_0)t}$$

we obtain classical Doppler shift, which depends on wire's rotation frequency, initial orientation and position of that infinitesimal dipole relatively to the center of rotation.

Fast rotating objects

As soon as the wire's rotation period becomes comparable with radar observation interval, not only linear terms in the serial expansion have to be taken into consideration, and this expansion becomes not convenient to use for close solution analysis. For this case we can use relation

$$e^{\frac{1}{2}z\left(t-\frac{1}{t}\right)} = \sum_{k=-\infty}^{\infty} t^k J_k(z), \quad t \neq 0$$

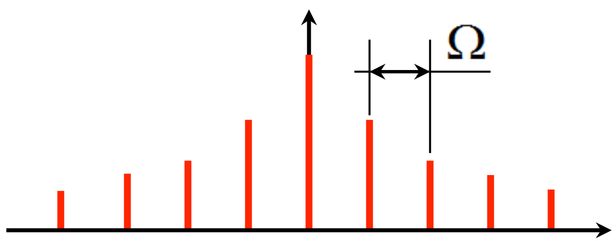
where $J_k(z)$ are the Bessel functions of integer order *k*.

Defining $t = e^{j\Omega t}$, assuming without loss of generality $\theta_0 = 0$, and using the fact that

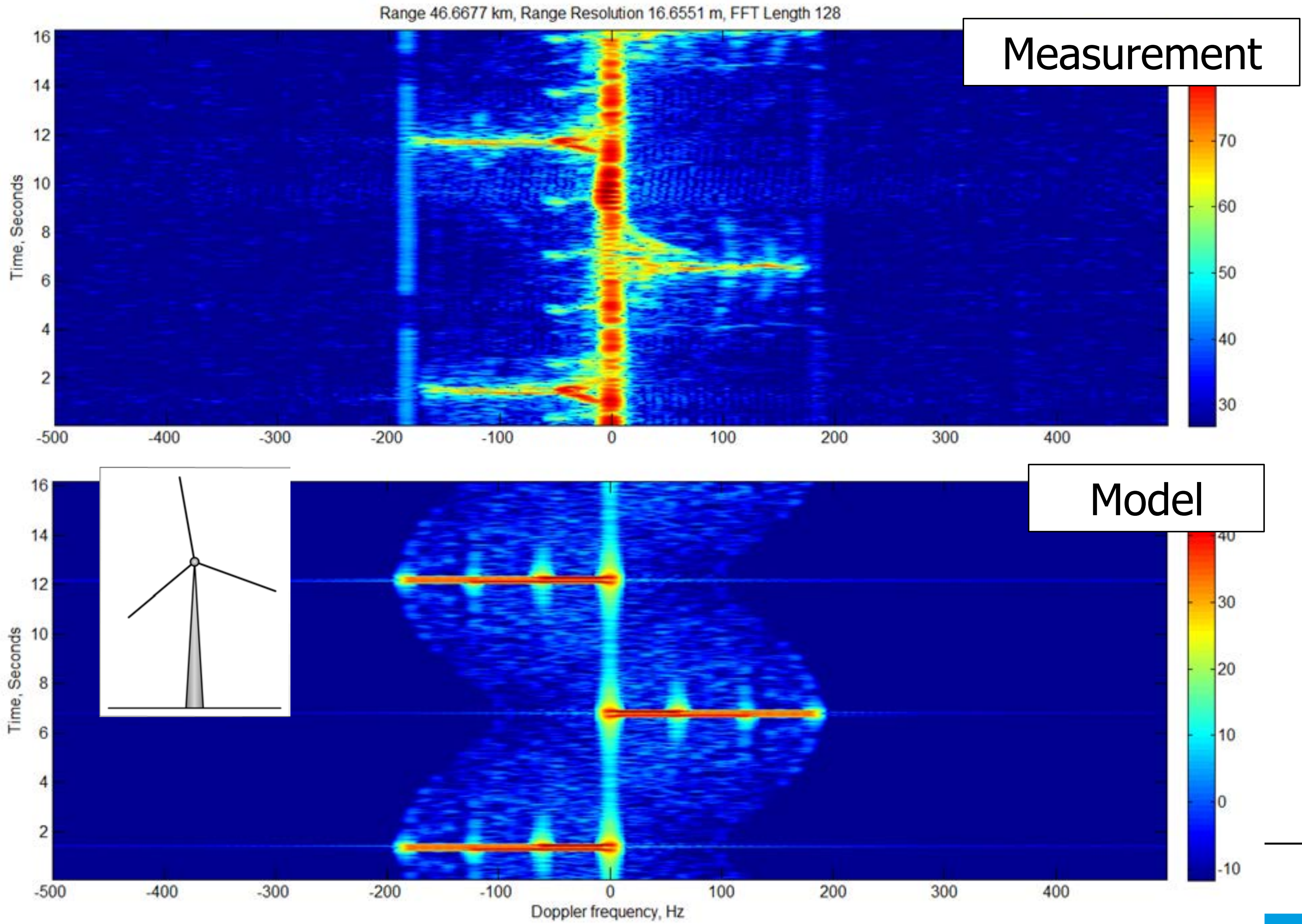
$$\cos x = \sin(x + \pi/2)$$

we have as result

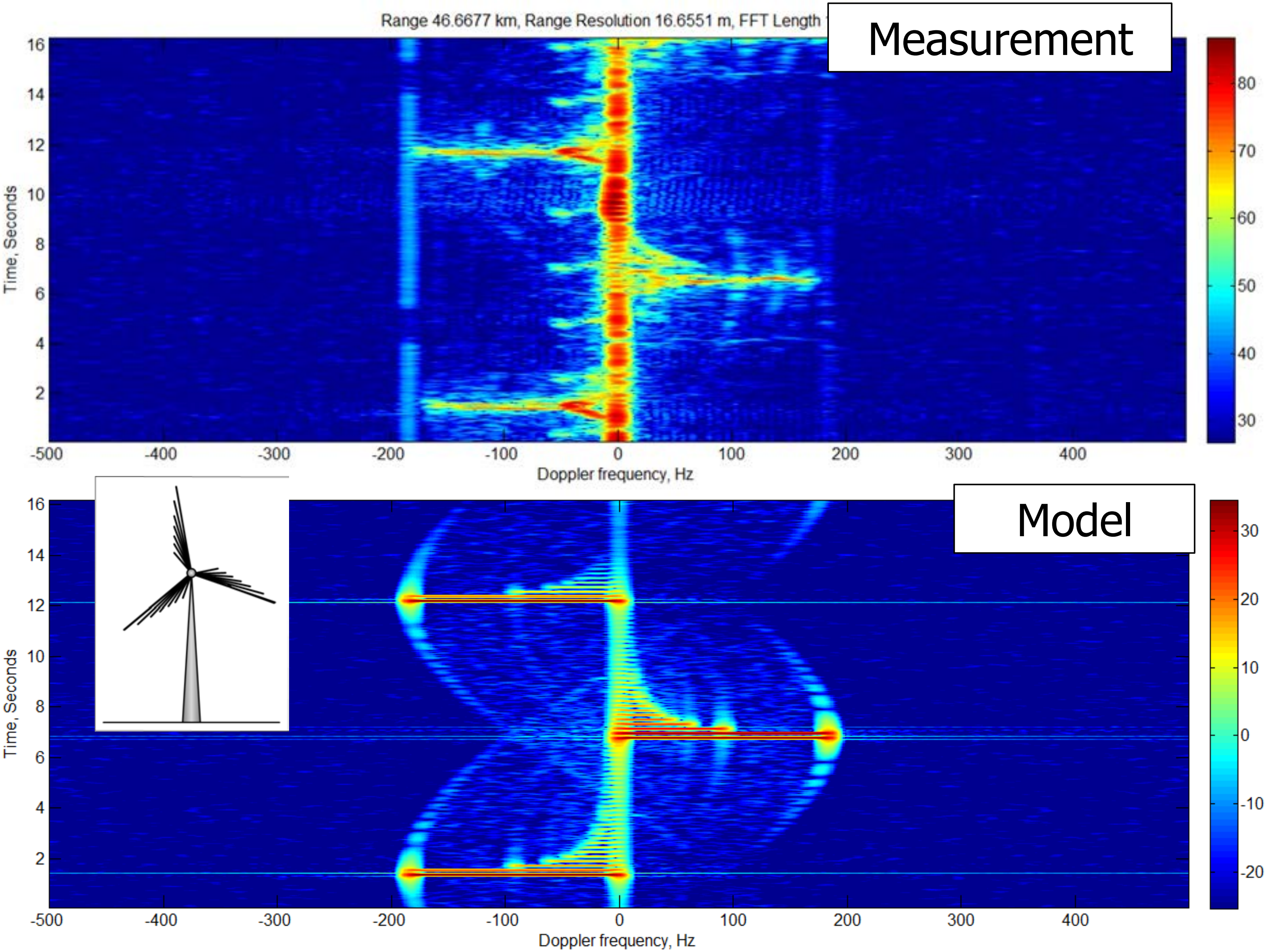
$$e^{jkz'\cos\Omega t} e^{j\omega t} = e^{j\omega t} \sum_{k=-\infty}^{\infty} e^{j\frac{\pi n}{2}} J_k(kz') \cdot e^{j\Omega kt}$$



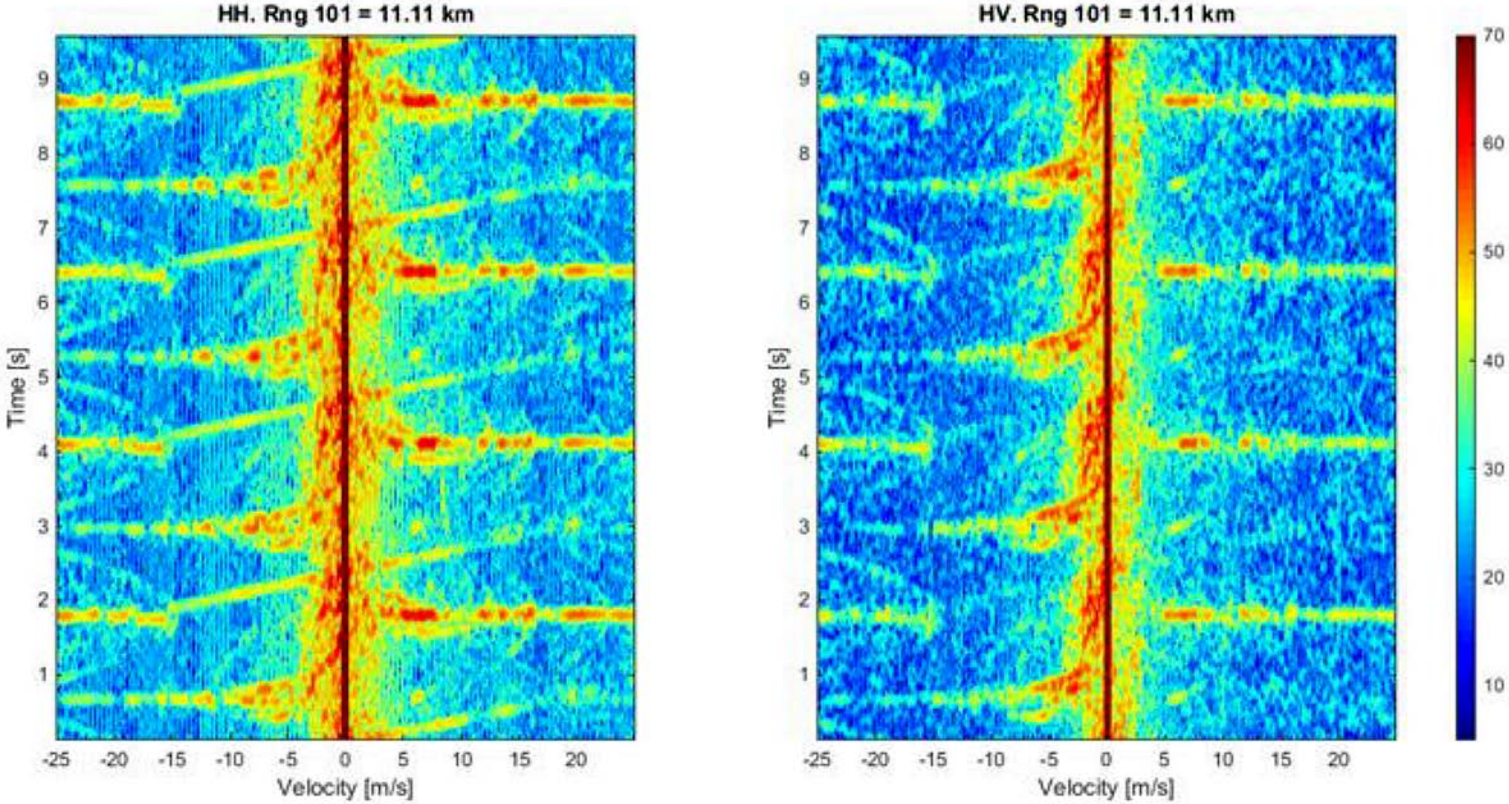
Comparison of model and observations



Comparison of model and observations



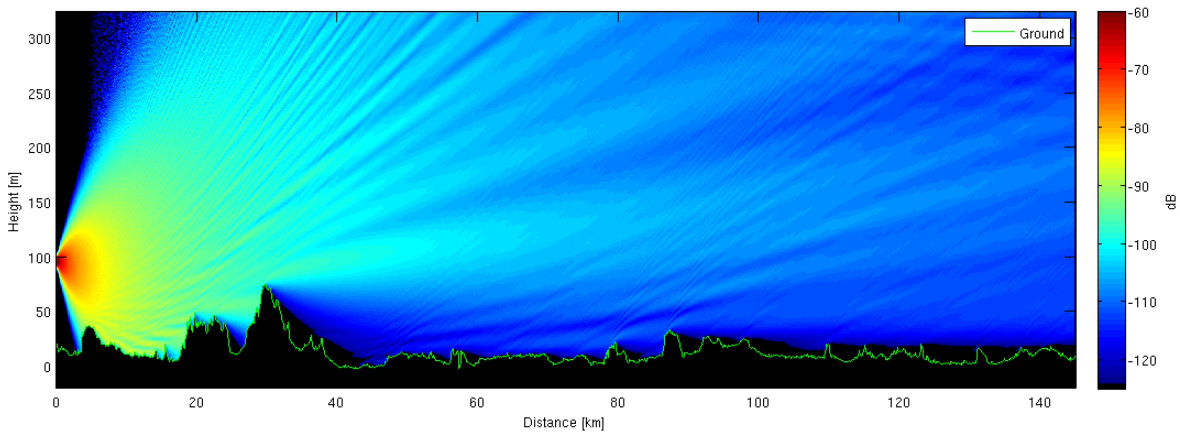
Further development of the model

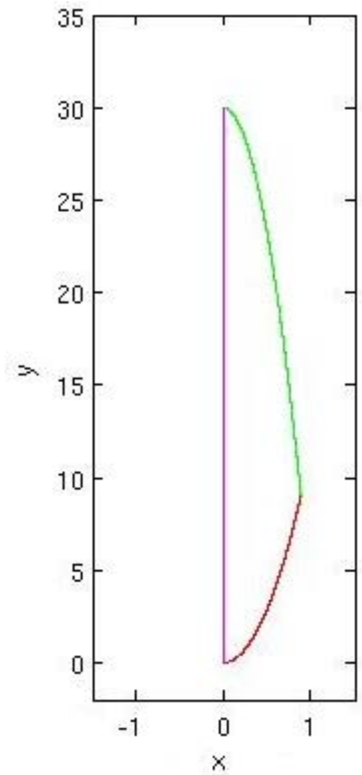


- Amplitude modulation of Doppler flushes
- Non-linear elements of wire structure
- Low frequency extension – mono- and bi-static case
- Simulation of Range profile

Multipath effects and realistic shape of a blade

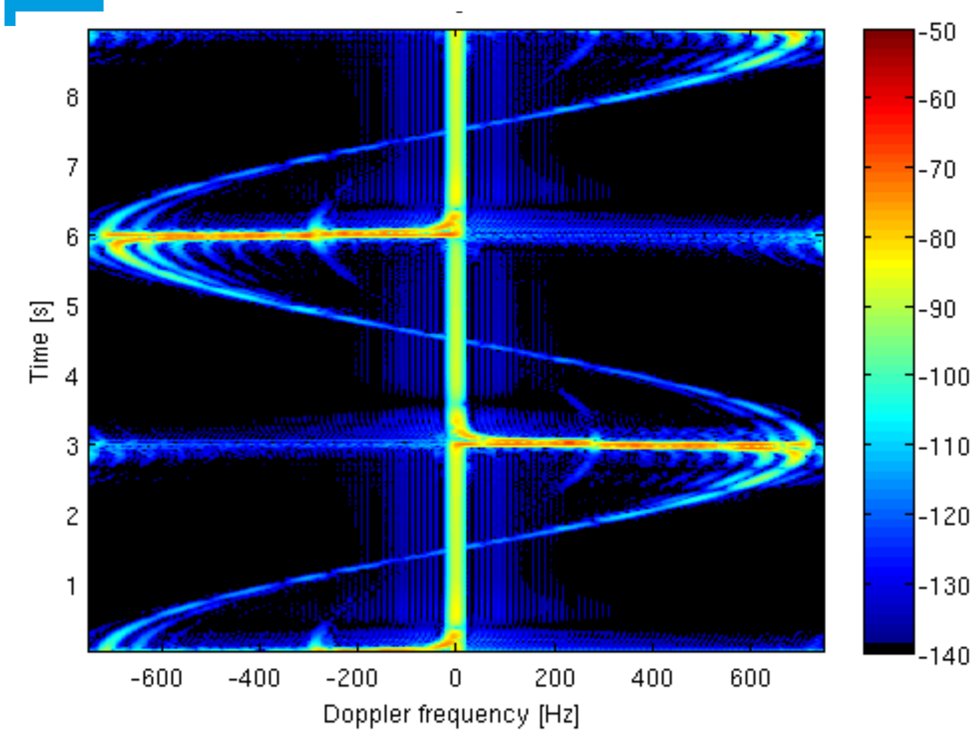
Use of parabolic equation method to describe the radar signal interactions with a ground surface (multipath)

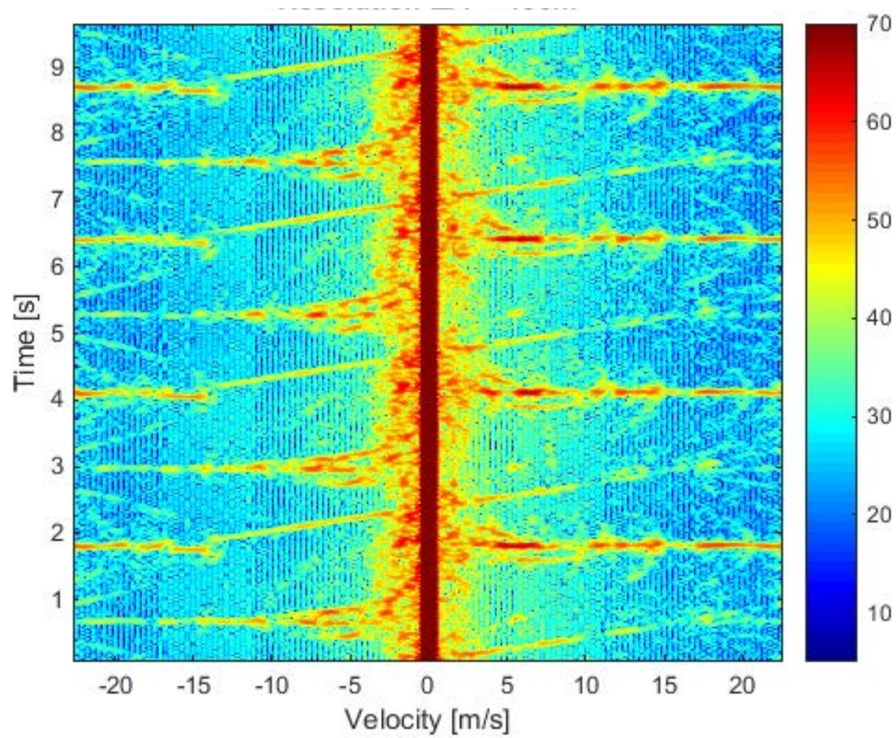




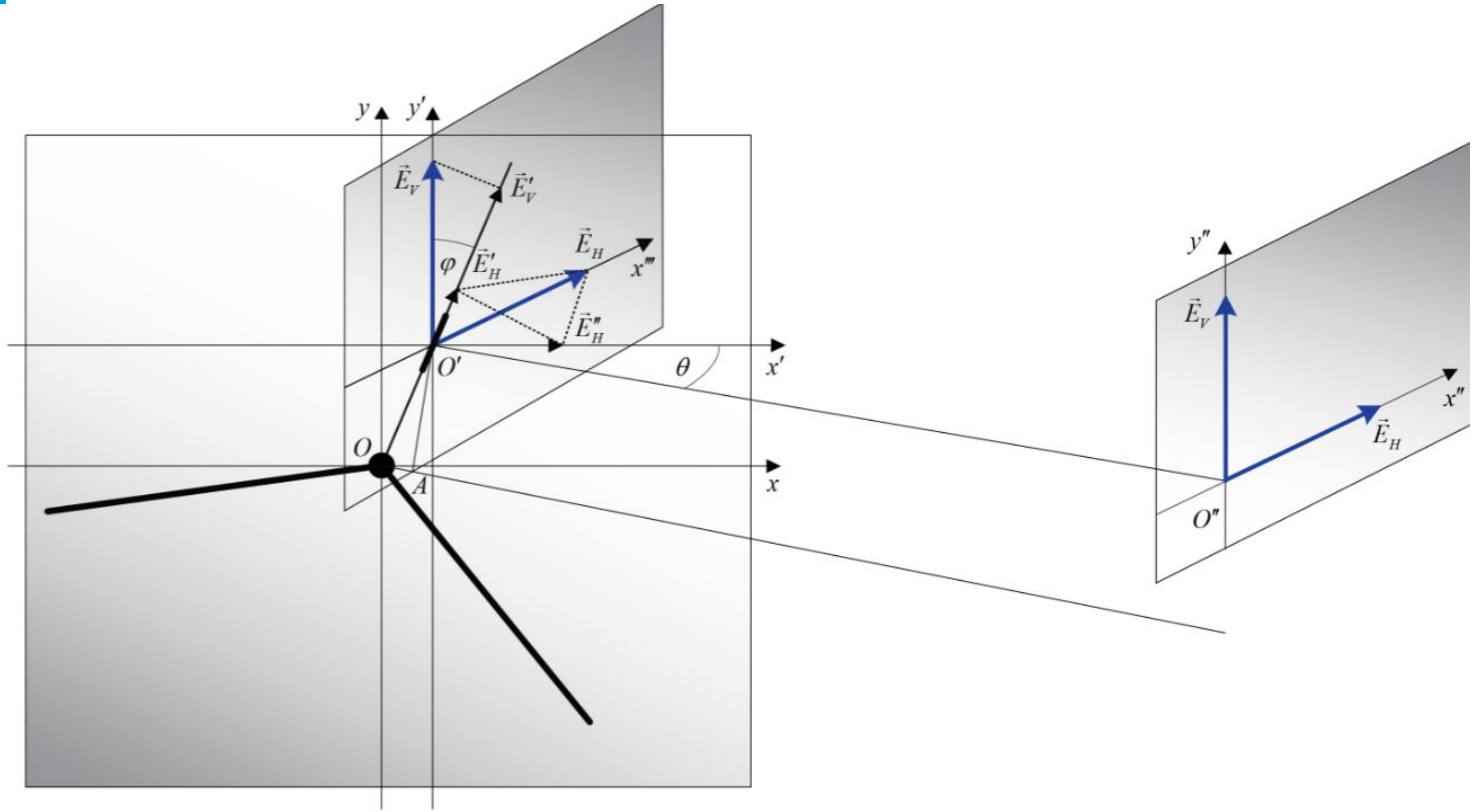
Linear wire structure is a good model approximation for low frequencies.
But when the wavelength become shorter, the shape of the blade influences backscattered signals.

Multipath effects and realistic shape of a blade





Low-frequency polarimetric extension



Monostatic case

The backscattered field are evaluated and then the resulting scattering matrix

$$\begin{bmatrix} E_V^S \\ E_H^S \end{bmatrix} = A(z') \begin{bmatrix} S_{VV} & S_{VH} \\ S_{HV} & S_{HH} \end{bmatrix} \begin{bmatrix} E_V^T \\ E_H^T \end{bmatrix}$$

$$dS(\phi, \theta, z') = A(z') \begin{bmatrix} \cos^2\phi(t) & \cos\phi(t)\sin\phi(t)\sin\theta \\ \cos\phi(t)\sin\phi(t)\sin\theta & \sin^2\phi(t)\sin^2\theta \end{bmatrix} dz'$$

where

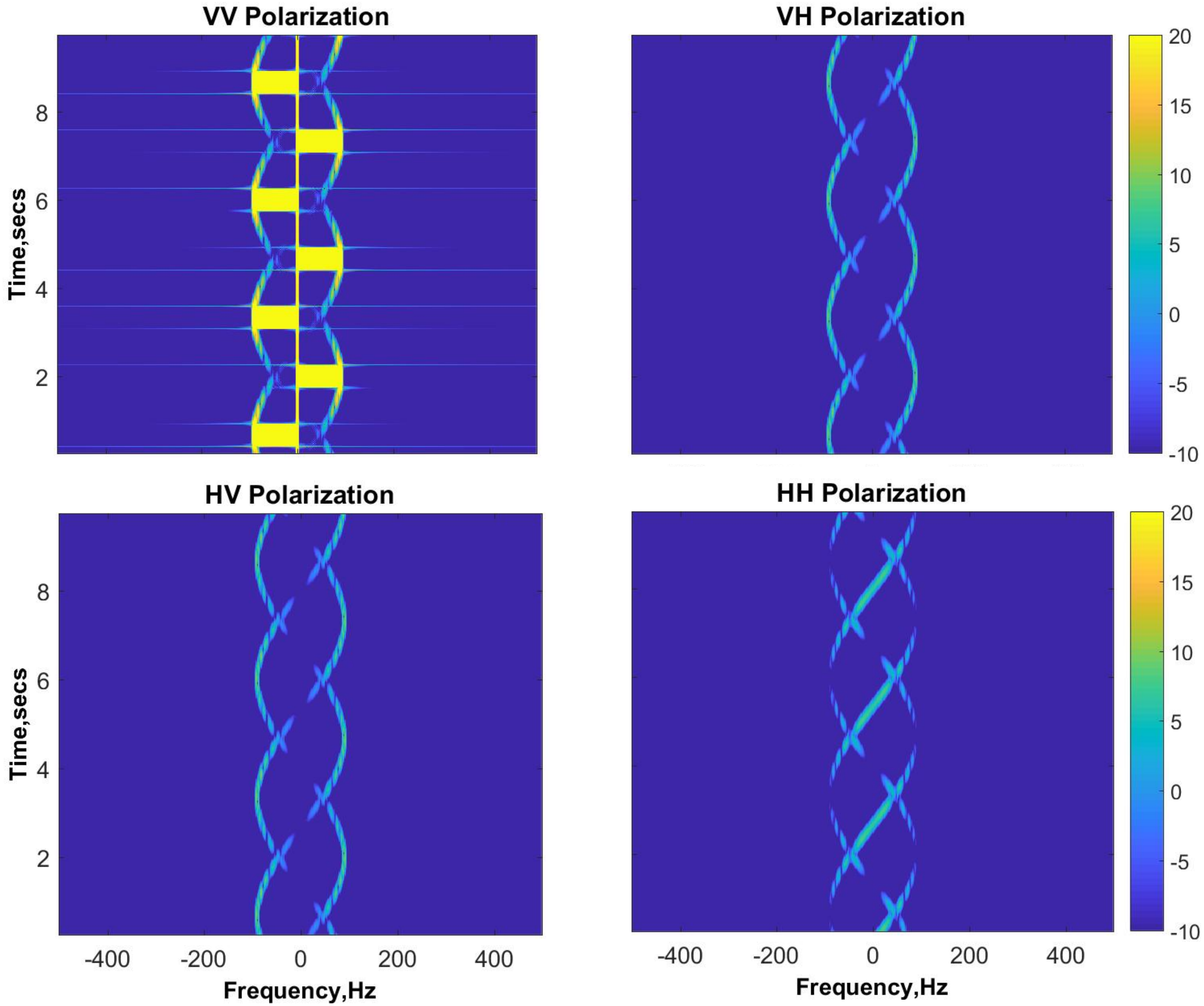
$$A(z') = j\eta \frac{e^{-jkz_0}}{4\pi z_0} . e^{+j2kz' \sin\phi(t)\cos\theta}$$

The total E-field can be calculated by integrating the scattering matrix for the length of the blade length

$$\mathbf{E}^S = \left\{ \sum_{n=1}^{3} \int_0^L \mathbf{S}(\phi + \Delta\phi_n, \theta, z') dz' \right\} \mathbf{E}^{\mathbf{T}}$$

A mono-static example at 600 MHz

Aspect angle θ = 60°



Bi-static case

- Bi-static scattering case depends upon the incident angle and the scattering angle.
- The scattering matrix is

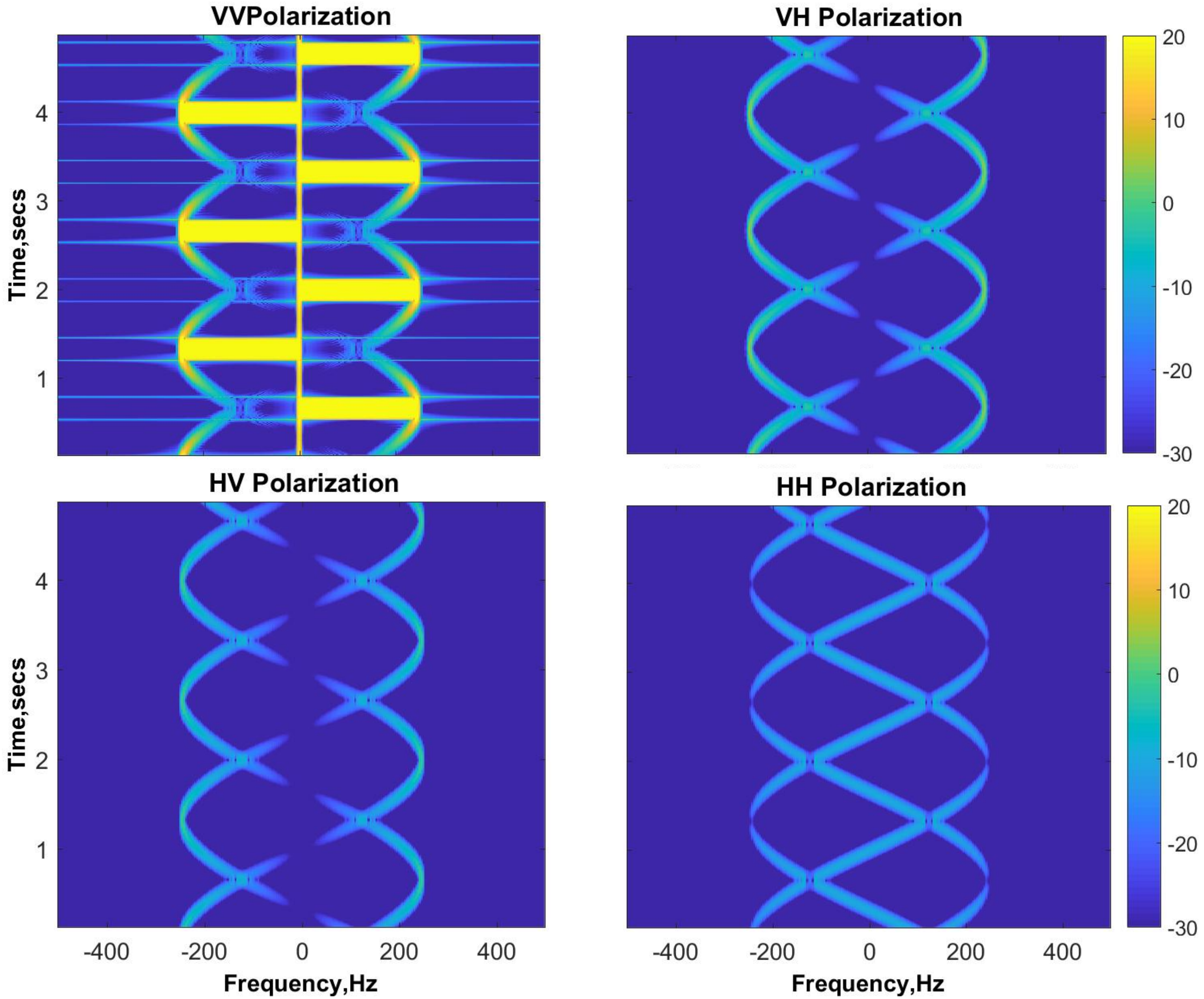
$$dS(\phi,\theta,z') = A(z') \begin{bmatrix} \cos^2\phi(t) & \sin\phi(t)\cos\phi(t)\sin\theta_i \\ \sin\phi(t)\cos\phi(t)\sin\theta_s & \sin^2\phi(t)\sin\theta_s\sin\theta_i \end{bmatrix} dz'$$

where

$$A(z') = j\eta \frac{e^{-jkz_0}}{4\pi z_0} . e^{+jkz'\sin\phi(t)(\cos\theta_i + \cos\theta_s)}$$

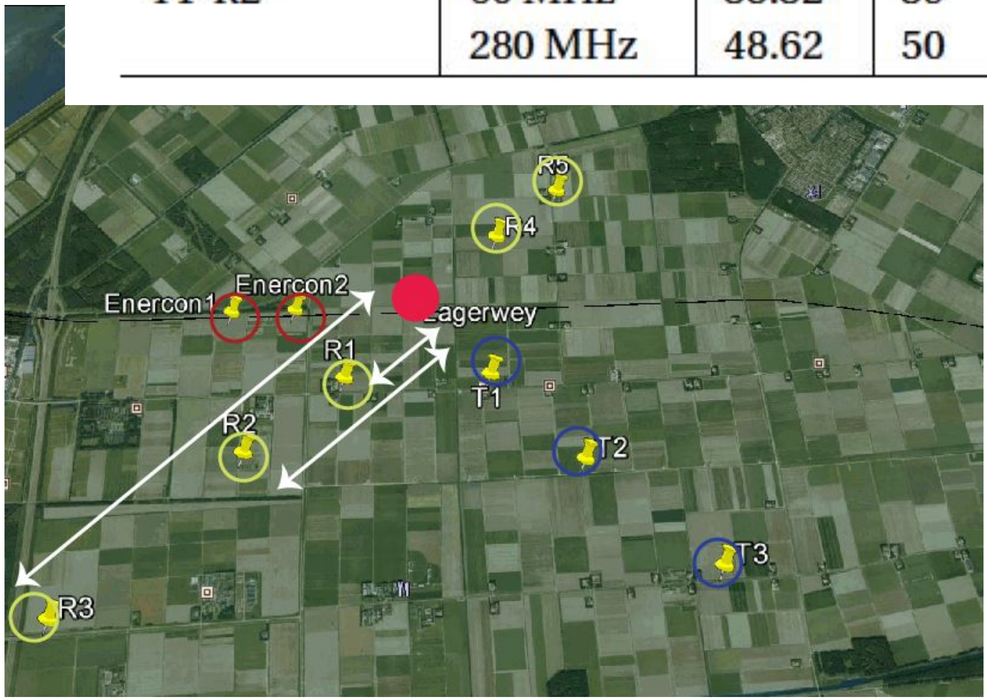
A bi-static example at 600 MHz

Aspect angles:
$\theta_i = 30°$
$\theta_s = 60°$



Comparison with experiment

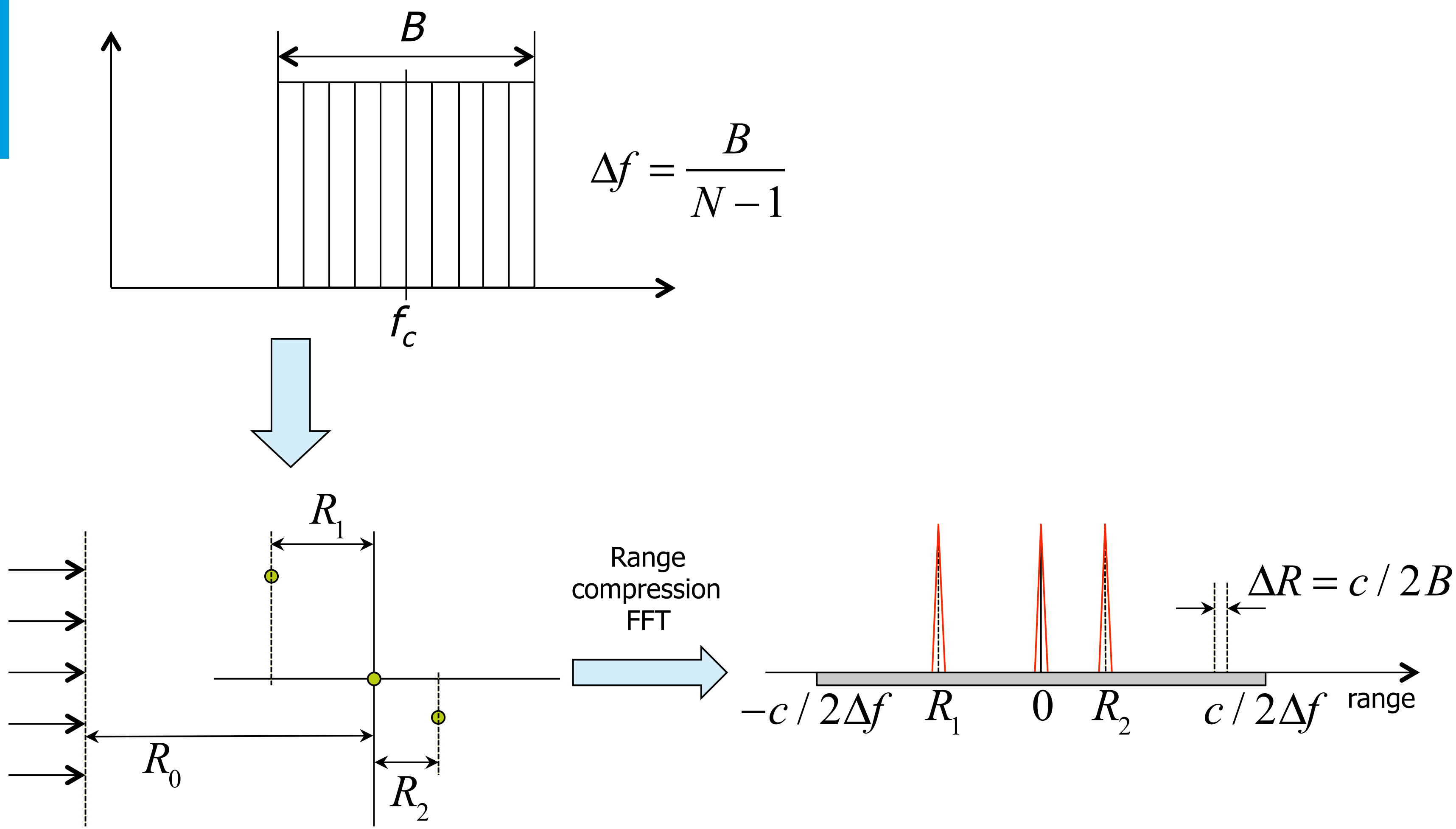
Configuration	Frequency	Signal Strength		Difference		Error(dB)
		Model	Measured	Model	Measured	
T1-R1	200 MHz	15.88	40			
	600 MHz	25.37	57	19.08	17	2.8
T2-R2	235 MHz	8.02	53			
	605 MHZ	15.94	67	16.06	14	2.06
T1-R2	60 MHz	35.32	39			
	280 MHz	48.62	50	26.6	11	15.6



Bistatic measurements by the Radiocommunications Agency Netherlands.

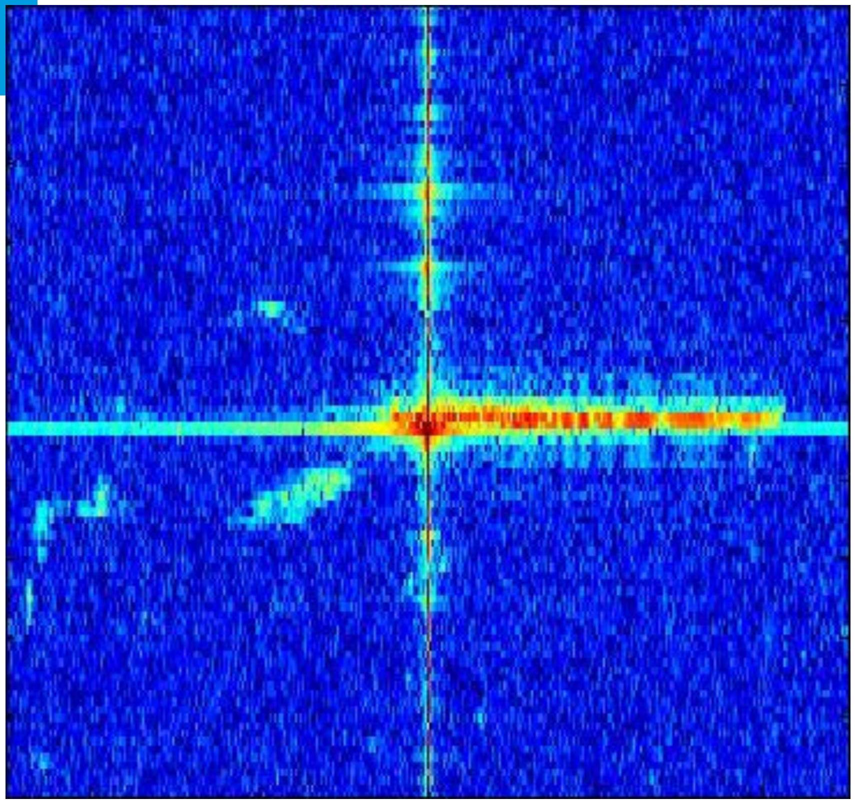
Our acknowledgements to Loek Colussi.

Simulation of WT's Range profile

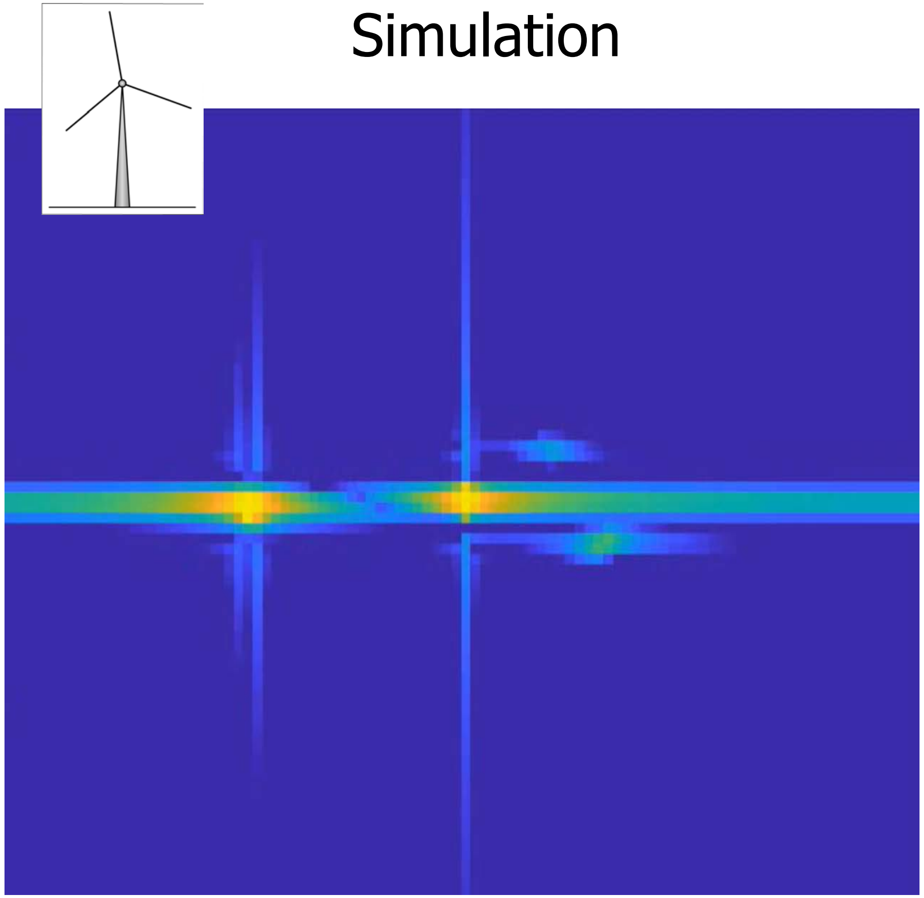


Range profiling results

PARSAX radar



Simulation



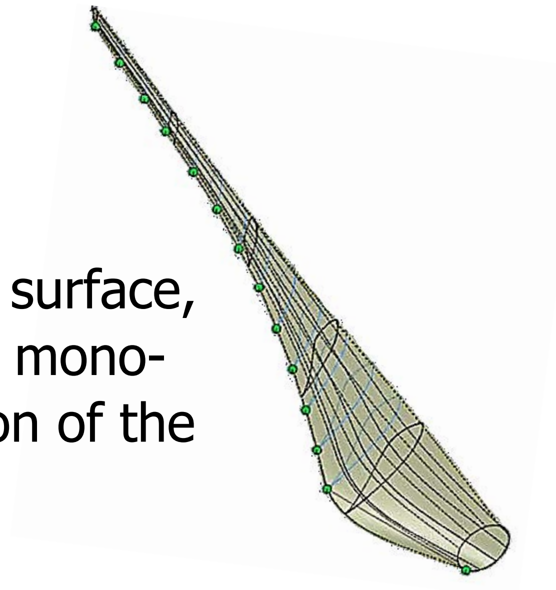
S-band, 50 MHz bandwidth

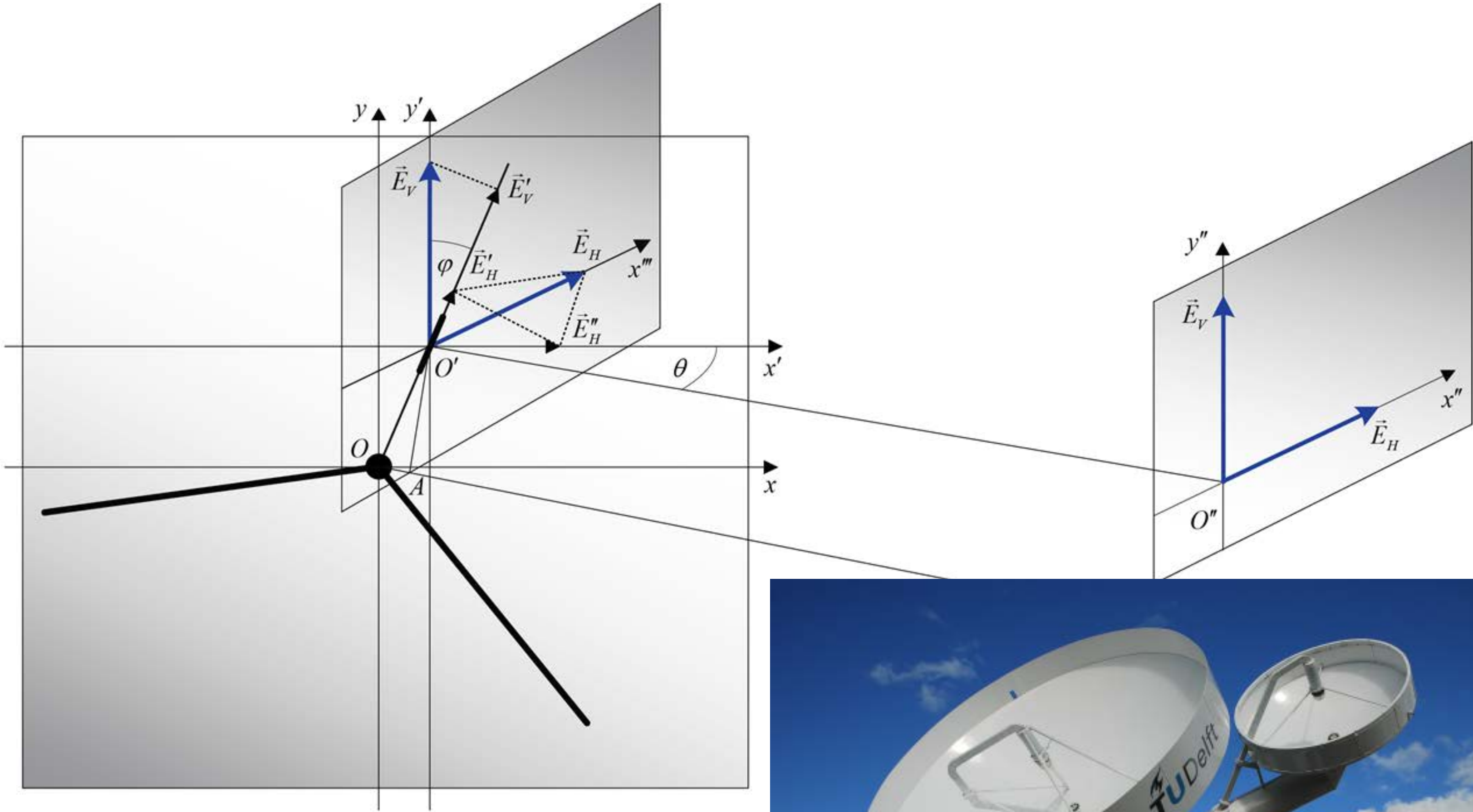
Conclusions

- The simplest model of wind turbines as slowly rotating linear wired construction provides the possibility to reproduce and analyze main micro-Doppler characteristics of wind-turbines.

- To stay in velocity domain it is necessary during the simulation or measurement interpretation to take into account the relation between wind turbine's rotation period and radar's observation time

- The model of wind turbines as slowly rotating linear wired construction has been extended with capability to simulate the influence of the ground surface, range profiling and low-frequency polarimetry for mono- and bi-static cases. Has been done initial validation of the model with experimental data.




y
y′
$\vec{E}_V$
$\vec{E}'_V$
$\vec{E}_H$
x'''
φ
$\vec{E}'_H$
$\vec{E}''_H$
O′
θ
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O
A
x
y″
$\vec{E}_V$
x″
$\vec{E}_H$
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Questions?