



## 2. PATH LOSS AND TIME FREQUENCY SPECTRUM DETERMINATION

Figure 1(a) shows a WT obstructing a radio link. We assume the simplest interference scenario of a signal path cutting the plane of obstruction inside the upper half of rotor swept area (above nacelle) [5]. The signal is periodically obstructed by the rotating blades and hence a time variant Doppler deviation of the received signal is observed. The impact of the static WT tower is neglected. For the simplification of calculations, the blades are assumed to be of rectangular shape in the plane of obstruction. Furthermore, only a single blade with infinite length is considered for the aforementioned simplest interference scenario. We use a one dimensional Fresnel diffraction approximation along a horizontal axis perpendicular to the line-of-sight path (Figure 1(b), origin of  $x$ - and  $y$ -coordinate aligned with the axis of the signal path in the plane of obstruction) [6].

The amplitude of the electric field at a target located on the axis of the signal path is given by

$$E_p = \frac{E_u}{\sqrt{2}} \{ [C(\nu) - jS(\nu)]_{\nu_{b2}}^{+\infty} + [C(\nu) - jS(\nu)]_{-\infty}^{\nu_{b1}} \} \quad (1)$$

where  $E_u$  is the electric field amplitude at the target in the absence of the obstruction.  $C$  and  $S$  are the well-known Fresnel integrals.  $\nu$  is a dimensionless aperture coordinate given as

$$\nu_{x1/2} = \left[ -\sqrt{x_0^2 + y_0^2} \cdot \sin \left( \phi + \arctan \frac{x_0}{y_0} \right) \pm \frac{w_b}{2} \right] + \sqrt{\frac{2}{\lambda} \left( \frac{1}{d_1} + \frac{1}{d_2} \right)} \quad (2)$$

where  $d_1$  is the distance between the radar site and the WT,  $d_2$  is the distance between the WT and the target,  $\lambda$  is the wavelength of the radar signal,  $x_o$  and  $y_o$  are the coordinates at the rotor axis and  $w_b$  is the blade width. The  $+$  sign is applicable for  $v_1$  and the  $-$  sign for  $v_2$ . A detailed description of this approach can be found in [7]. The results obtained are verified with 3D field solver using Uniform Theory of Diffraction (UTD) method and software package FEKO. The time frequency spectrum is obtained by the short time fourier transform (STFT) of the received time domain signal.

## 3. RESULTS AND DISCUSSION

The diffraction path loss is calculated at a frequency of 1.30 GHz, which is typically used for weather radars. The WT model used for this investigation has three blades, each with a length of 64 m. The width of the blade at the point where the signal path cuts through the plane of obstruction is assumed to be  $w_b = 1.5$  m. A blade rotation speed of 15 rpm is assumed. The signal path is set to be 60 m above the rotor axis (close to the tip of the blade). The WT is at  $d_1 = 500$  m away from the transmitter and the receiver is located at 8000 m ( $d_2 = 7500$ ). The one way diffraction induced loss ( $\Delta\alpha d$ ) and the phase shift ( $\Delta\beta d$ ) at 1.3 GHz vs rotation angle  $\Phi$  are shown in Figures 2(a) and (b). For a radar system, these values have to be multiplied by a factor of 2. For  $\Phi = 0$  the upper blade is oriented vertically. At  $\Phi = 60^\circ$  this blade is as far from the axis of the signal path

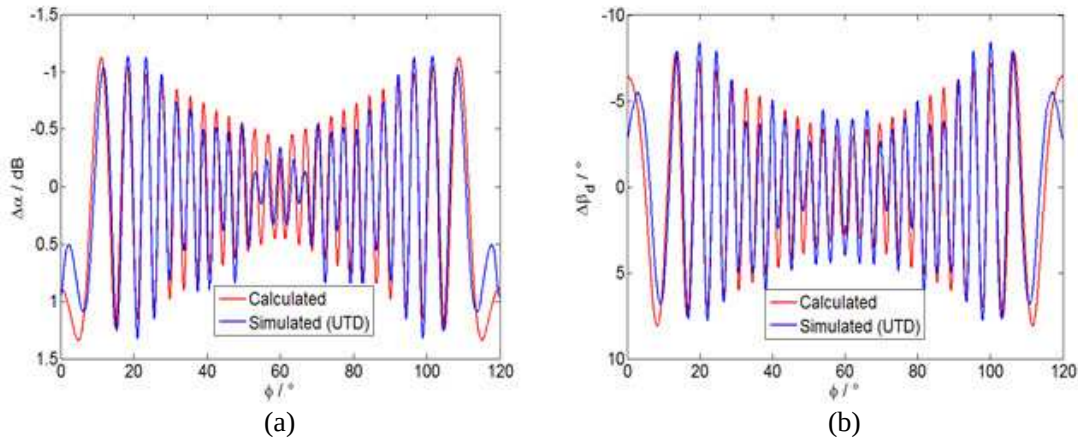


Figure 2: Impact of 3-blade rotor vs rotor angle  $\Phi$  at 1.3 GHz: diffraction induced one way (a) loss and (b) phase shift for  $d_1 = 500$  m and  $d_2 = 7500$  m.

as the next blade following in clockwise direction. Thus, all graphs show an even symmetry along  $\Phi$  for every  $60^\circ$ . The calculated values are verified by comparison with UTD simulation results obtained by software package FEKO.

The comparison in Figure 2 shows a slight disagreement between the calculated and simulated curves. This can be attributed to the scattering at the edges of the blade, which is not considered in our theoretical approach. Moreover, FEKO simulations are carried out with three rotor blades, whereas, the theoretical model only considers a single infinite long blade. At values of  $\Phi$  around  $60^\circ$ , the next blade which is not considered in the theoretical model is approaching the line of sight and hence diffraction effects of both the blades appear to be significant rather than just the one accounted for. However, for most values of  $\Phi$ , the two results agree with each other.

Figure 3 shows the maximum value of  $\Delta\alpha_d$  for values of  $d_1$  ranging from 500 m to 7500 m. The distance of the WT from the transmitter ( $d_1$ ) is varied keeping the overall link distance constant at  $d_1 + d_2 = 8$  km. The lowest value of diffraction loss is observed when the WT is located midway between the transmitter and the receiver ( $d_1 = d_2 = 4000$  m). As the location of the WT is moved closer to either the transmitter or the receiver, the diffraction loss starts to increase. Due to symmetry,  $d_1$  and  $d_2$  can be interchanged. This underlines the importance of keeping the WT considerably far from a communication system.

The Doppler deviation introduced by the rotating blades can be characterized by the time frequency spectrum of the received signal. A Hamming window of 256 samples for a sampling frequency of 1 kHz is used to obtain the STFT of the received time domain signal. Figure 4 shows the spectrum of the received signal ( $d_1 = 500$  m,  $d_2 = 7500$  m). For a rotational speed of 15 RPM, a single rotation of one blade is completed in 4 seconds. Noticeable sinusoidal tracks are visible. At low values of  $\Phi$ , one blade is in close proximity to the line of sight, obstructing the first few Fresnel zones. This gives rise to a strong low frequency component. As the blade rotates, its distance from the signal axis increases and it is cutting through a higher order Fresnel zones at a given time span, introducing higher frequency components with a peak occurring at  $\Phi = 60^\circ$ . Beyond this angle, the next blade starts approaching the line of sight, moving towards Fresnel zones of larger sizes (lower order Fresnel zones) thus introducing more components of lower frequencies. Overall, a significant

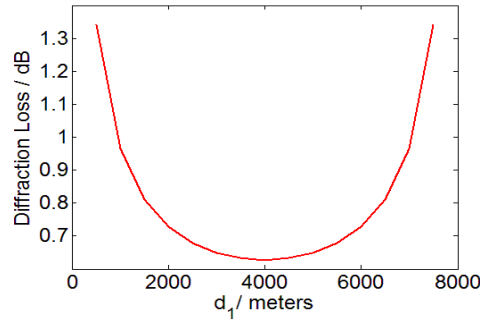


Figure 3: Variation of maximum one-way diffraction loss with changing values of  $d_1$ .

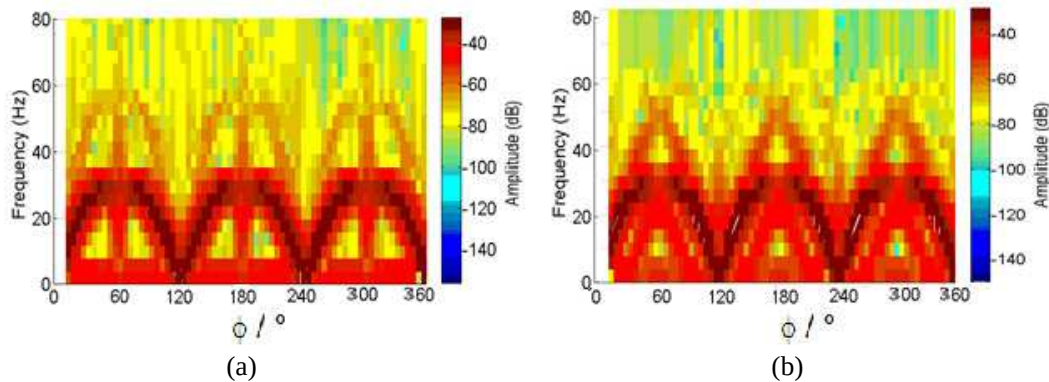


Figure 4: Two-Way Normalized time-frequency spectrum at 1.3 GHz for  $d_1 = 500$  m and  $d_2 = 7500$  m. (a) Calculated. (b) Simulated.

Doppler deviation of up to 55 Hz is observed. For a Doppler radar, this corresponds to a target velocity of 6.3 m/s. A weather radar, like all Doppler radars, relies on Doppler-shifted radar returns for the estimation of wind speed. Doppler deviation caused by WT blades will therefore lead to inaccurate wind measurements.

The investigations presented in this paper so far have ignored the ground plane effects. 3D radars like weather radars are less susceptible to the ground plane reflections, owing to their extremely narrow beams. However, the ground plane effects become significant for 2D radar systems and fixed radio links and hence must be taken into account. Figures 5(a) and (b) compare  $\Delta\alpha_d$  and  $\Delta\beta_d$  with and without the presence of a ground plane, for the same set of parameters described earlier. These values are obtained by UTD simulations. Higher values of  $\Delta\alpha_d$  and  $\Delta\beta_d$  are observed if the ground plane is accounted for. This results in an even stronger Doppler deviation compared to the case where the ground plane is neglected.

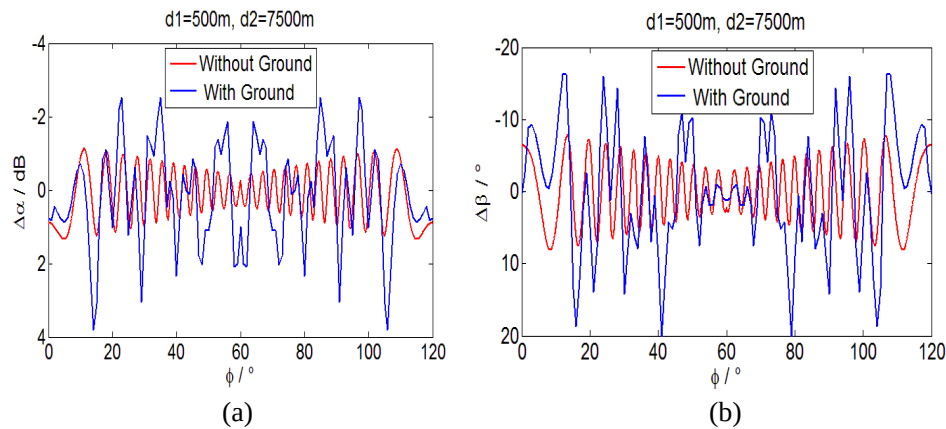


Figure 5: Impact of 3-blade rotor vs rotor angle  $\Phi$  at 1.3 GHz, with and without ground plane: simulated diffraction induced (a) loss and (b) phase shift for  $d_1 = 500$  m and  $d_2 = 7500$  m.

#### 4. CONCLUSIONS

One-dimensional Fresnel diffraction approach has been applied to calculate the impact of diffraction on the amplitude and phase of the WT forward scattered signal. Furthermore, deviation of the Doppler spectrum caused by the time variant amplitude and phase modulation of the two-way signal is presented. A joint time-frequency analysis of the diffracted signal has been performed using STFT to highlight the motion dynamic Doppler features. It has been demonstrated that a Doppler deviation of up to 55 Hz will occur in the forward scatter region for radars operating at 1.3 GHz. For the characterization of the WT forward scatter in the presence of a ground plane, a thorough investigation needs to be carried out by placing the WT at different locations along the radio link. Different transmitter and receiver orientations for varying antenna height and signal path also need to be considered for outlining the worst case scenario of WT interference. Moreover, the impact of multiple wind turbines has to be further investigated. An extension of the presented study has to be investigated.

#### REFERENCES

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