Wind project Gent

Groep Blockmans Green

Simple Engineering Assessment RADAR

Intersoft Electronics Services
services@intersoft-electronics.com
IES-23754

Version Control

Date	Status	Authority	Signature
8 Dec 23 v0.1	Draft	Terence Hunter, ing. Service Technician	
11 Dec 23 v1.0	Review	Mattijs Hertsens, ir. Project Manager	

Contents

1. List of Abbreviations

AGL .... Above Ground Level

AMSL .... Above Mean Sea level

ASR .... Airfield Surveillance Radar

BAF .... Belgian Air Force

CFAR .... Constant False Alarm Rate

dBsm .... Decibel Per Square Meter [$10 \log_{10} (\frac{RCS}{m^2})$]

DEA .... Detailed Engineering Assessment

LoS .... Line of Sight

MoD .... Ministry of Defence

MTD .... Moving Target Detector

MTI .... Moving Target Indication

NM .... Nautical Miles

Pd .... Probability of Detection

PSR .... Primary Surveillance Radar

RADAR ..... Radio Detection and Ranging

RAG .... Range-Azimuth Gating

RCS .... Radar Cross Section

RF .... Radio Frequency

SEA .... Simple Engineering Assessment

SRTM .... Shuttle Radar Topography Mission

SRE .... Surveillance Radar Equipment

SSR .... Secondary Surveillance Radar

STC .... Sensitivity Time Control

TA .... Terminal Approach

VCC .... Vertical Clutter Canceller

WT .... Wind Turbine

2. Introduction

Wind development located within line of sight of radar systems (LoS) can cause clutter and interference resulting in significant performance degradation. As wind turbines continue to be installed (more and bigger), and as advances in wind energy technology enable wind farms to be deployed in new regions of the country, the probability for wind development to present conflicts with radar missions related to air traffic control, weather forecasting, homeland security, and national defense is also likely to increase, as is the potential severity of those conflicts.

2.1 Wind turbine project

The project on behalf of **Groep Blockmans Green** concerns the following proposed wind turbine located near **Gent**, all coordinates are in Lambert72, the dimensions in this table are the maximum dimensions for this project (worst case scenario from radar point of view):

Turbine	**X**	**Y**	**Tip Height**	**Hub Height**	**Rotor ∅**
GBG1	109668	201947	210m	129m	163m

Table 2.1: Turbine under test

The turbine under test is visualised in the picture below.

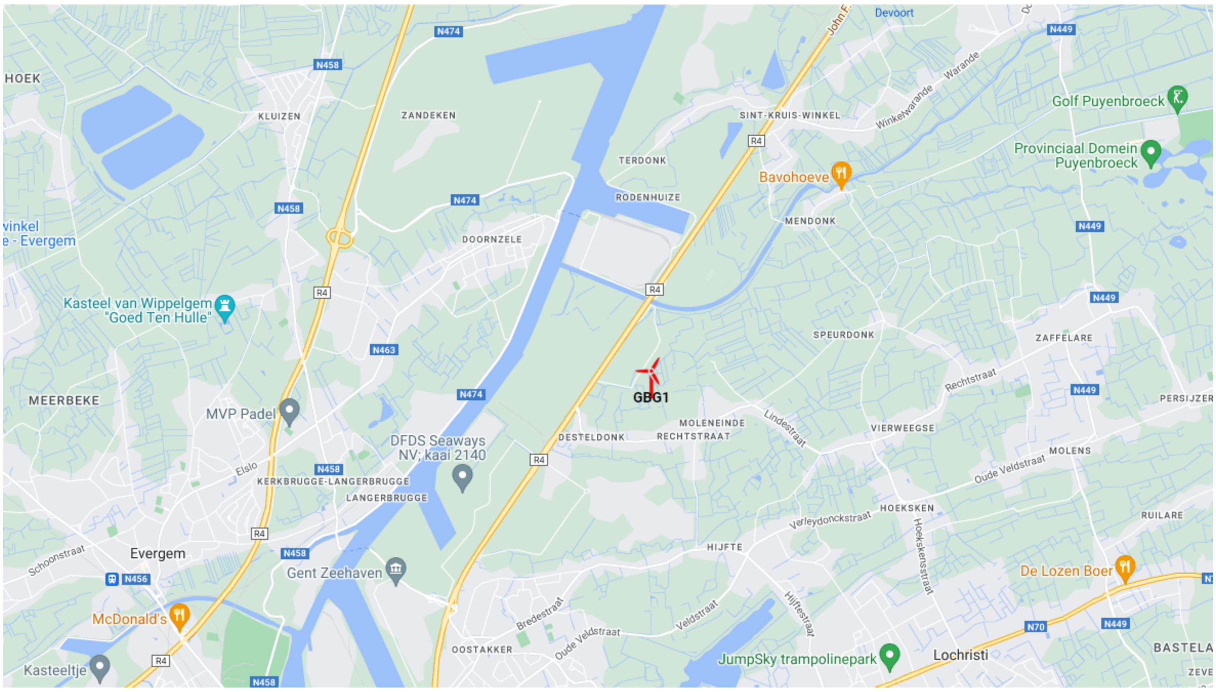

Figure 2.1: Geographical representation of the turbine under test

Taking into account the location and height of the turbine, a SEA for the following BAF radar system is required:

- S723 Semmerzake

Turbine	**Distance [NM]**	**Distance [km]**
GBG1	12.06	22.33

Table 2.2: Distance between the turbine under test and the Semmerzake radar

Tha table above gives an overview of the distance between this turbine and the radar system in nautical miles and kilometers (*1NM=1.852km/1km=0.539NM*).

2.2 Radar specifications

The radar specifications that are taken into account are listed below, figure 2.2. The parameters have been provided or confirmed by the Belgian Ministry of Defence. The technical details have been omitted due to reasons of confidentiality.

Technical Specifications	**RADAR Semmerzake** 
Beams	8
Doppler Bins	16
Constant False Alarm Rate	✓
Max Instrumented Range (PSR)	256NM/474km
Frequency	L-Band
Next Generation Signal Processor	V1.0
Range Azimuth Gating	✓
Radar Configuration Type	S723 Long Range Marconi
Radar Propagation Type	Pulse-Doppler
Soft Sensitive Time Control	✓
Adaptive Vertical Clutter Cancellation	✓

Figure 2.2: Technical specifications BAF radar system under test

3. Scope

3.1 Eurocontrol requirements

Given that the project lies beyond 15km of the radar under assessment and in radar line of sight, MoD asks to perform a "Simple Assessment" (zone 3 in the figure below). This assessment, as detailed in section 4.3 of the EUROCONTROL [1] document, should be sufficient to enable the surveillance data provider to assess the situation.

Zone	Zone 1	Zone 2	Zone 3	Zone 4
Description	0 - 500 m	500 m - 15 km and in radar line of sight	Further than 15 km but within maximum instrumented range **and in** radar line of sight	Anywhere within maximum instrumented range but **not in** radar line of sight or outside the maximum instrumented range.
Assessment Requirements	**Safeguarding**	**Detailed assessment**	**Simple assessment**	**No assessment**

Figure 3.1: Eurocontrol requirements

A Secondary Surveillance Radar (SSR) assessment is out of scope for this study.

The scope for this project **Groep Blockmans Green, Gent** is thus as follows:

Impact	Reference [1]	Radar Semmerzake
Theoretical Analysis		
PSR probability of detection	4.1.1	✓
PSR false target reports	4.1.2	✓
PSR processing overload	4.1.3	✓
Practical Analysis		
Clutter Investigation	4.2.1	✓
Probability of Detection	4.2.2	✓

Figure 3.2: Scope of the study

A PSR simple engineering assessment is defined in the EUROCONTROL document to consist out of 3 parts. Each part will be further discussed in the theoretical analysis of the radar(s) under test.

For the practical analysis, the influence of surrounding turbine is investigated which consists of an analysis of the video data that is processed by the extraction chain of the radar system under test. In this analysis, the default signal processing chain is simulated to assess the contribution on the video data and target reports of operational wind turbines near the proposed wind project. The detection performance in the region of the wind project is also evaluated.

The general way of executing the SEA has been confirmed by MoD without remarks [7].

3.2 Obstacles in the vicinity

In this assessment, we take into account surrounding obstacles such as other wind turbines to evaluate the combined impact. For this we use an approximate 5-10 km radius. For this scenario, **44** other turbines have been identified, for more details see appendix A. These obstacles represent the worst case global effect with information coming from **Groep Blockmans Green**. These obstacles are a combination of existing turbines (green), permitted turbines (yellow) and turbines in application (magenta). These obstacles represent the worst case global effect, for more details see appendix A.

Scenario 1: Licensed Skalden Wind Turbines (8)

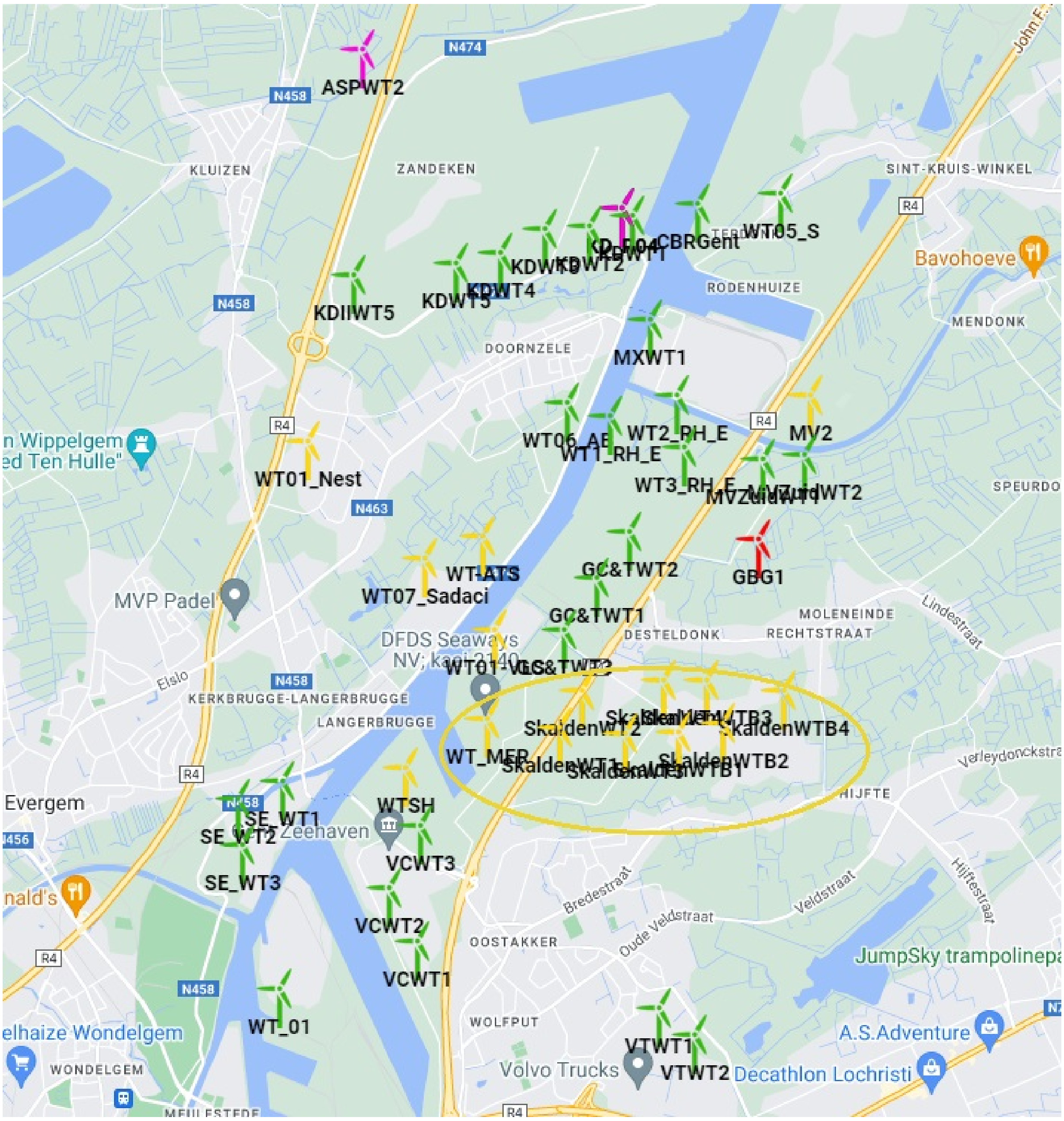

Figure 3.3: Obstacles around the turbine under test

Scenario 2: Application Skalden Wind Turbines (4)

40 other turbines have been identified for this scenario, for more details see appendix A.

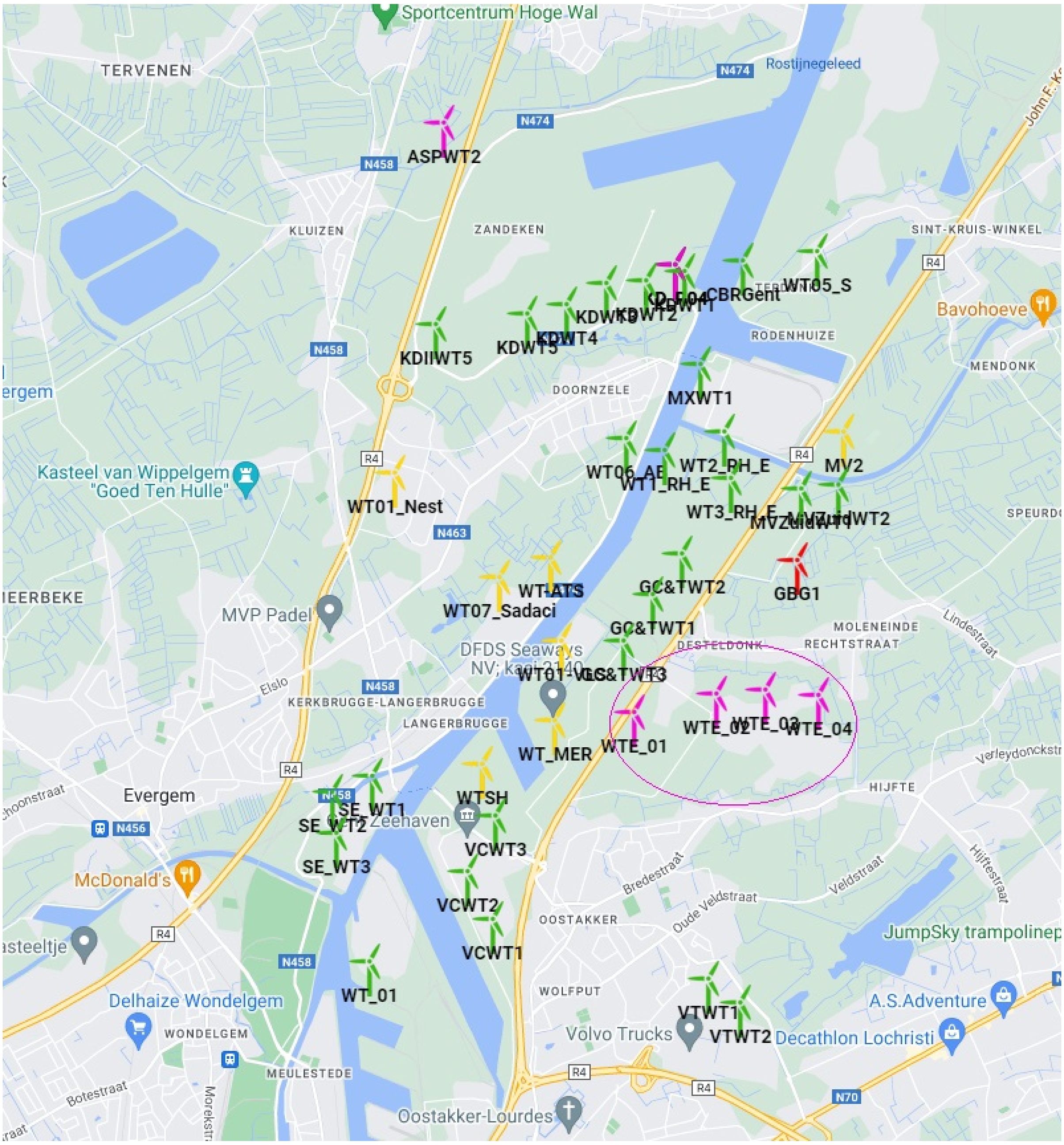

Figure 3.4: Obstacles around the turbine under test

4. Simple Engineering Assessment S723 Semmerzake

The general situation of the project is depicted here. The theoretical results will be verified with practical data. A geographic overview of the turbine under test and the Semmerzake radar is given below, figure 4.1. In red we see the turbine under test, in black the existing turbines and the black radar represents the Semmerzake S723 Long Range radar.

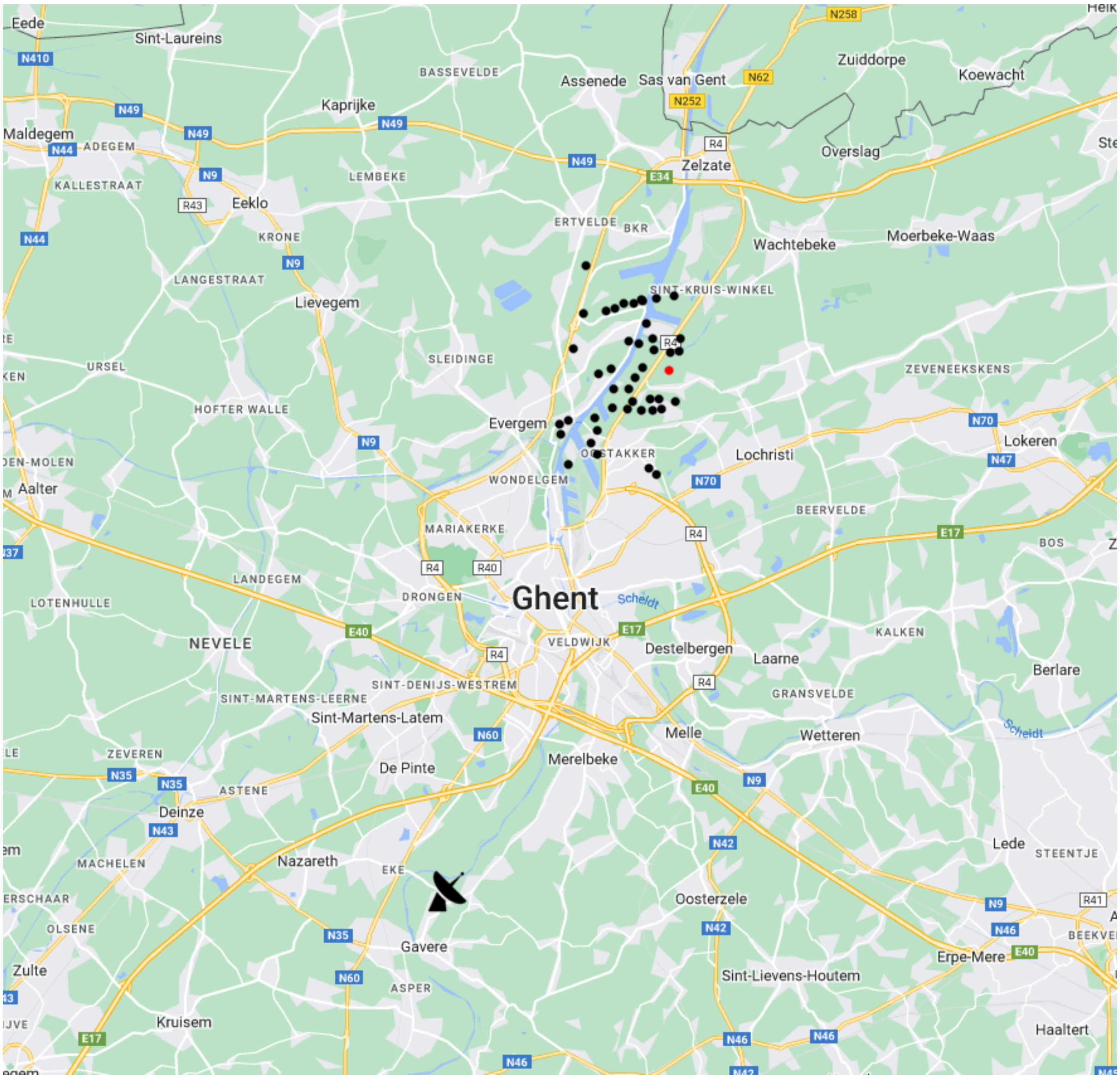

Figure 4.1: General overview with the Semmerzake radar

4.1 Theoretical analysis

A PSR simple engineering assessment is defined in the EUROCONTROL document to consist out of 3 parts, see also chapter 3 of this document:

- PSR probability of detection (subsection 4.1.1)
- PSR false target reports (subsection 4.1.2)
- PSR processing overload (subsection 4.2)

Each of these items will be discussed in detail below.

4.1.1 PSR Probability of detection

Semmerzake radar shadow

The following table gives information relative to the visibility of the turbine under test for the S723 Semmerzake radar system. If the tip height of a turbine is larger than the radar shadow, it is seen by the radar system. If the tip height of a turbine is larger than the radar shadow, but the radar shadow exceeds the hub height, only the rotor is seen by the radar. The calculations are given in table 4.1. Fore more information about radar shadow, see section D.1.

	Tip Height	**Hub Height**	**Blade Length**	**Shadow**	**Above LoS**
GBG1m	210m	129m	82m	5m	205m

Table 4.1: Turbine height above radar LoS

The turbine is 205m above the vertical line of sight of the radar, its dominant monostatic RCS component (hub) is in plain sight of the Semmerzake radar system.

Shadow Height Region

This chapter presents the effect of the shadow region in the vertical dimension due to signal blocking of the turbines under test. The figures below shows the shadow height generated by the turbine under test relative to the line of sight of the radar and the terrain profile. Fore more information about the shadow height region, see section D.1.

Full instrumental range

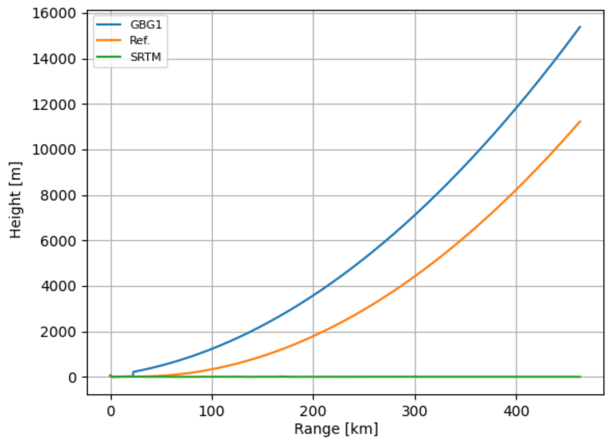

Figure 4.2: Wind Turbine 1

	Terrain shadow [m]	Turbine shadow [m]	Difference [m]
GBG1	11226	15385	4159

Table 4.2: Shadow height comparison at full instrumental range (256NM/474km)

Partial conclusion: At full instrumental range (256NM/474km) the average difference between the shadow height produced by the turbine under test and the radar line of sight in the vertical dimension is about **4158m** or **37%**.

Zoom 100km

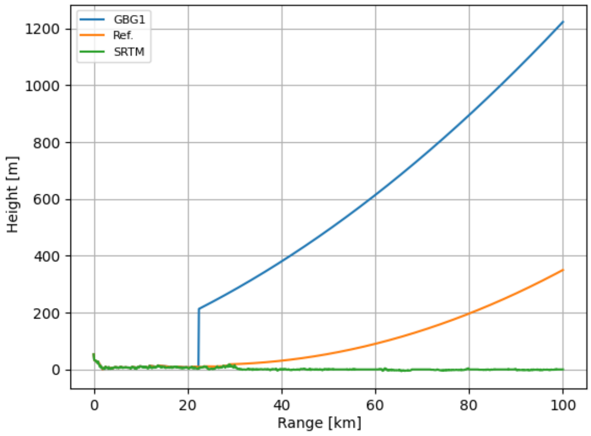

Figure 4.3: Wind Turbine 1

	Terrain shadow [m]	Turbine shadow [m]	Difference [m]
GBG1	350	1223	873

Table 4.3: Shadow height comparison at 100km

Partial conclusion: At 100km the average difference between the shadow height produced by the turbine under test and the radar line of sight in the vertical dimension is about **872m** or **249%**.

Shadow Width Region

In this chapter we calculate the three first Fresnel zones where destructive interference occurs (n = 1, 3 or 5).
The obtained result is presented in figure 4.4. Fore more information about the shadow width region, see section D.1.

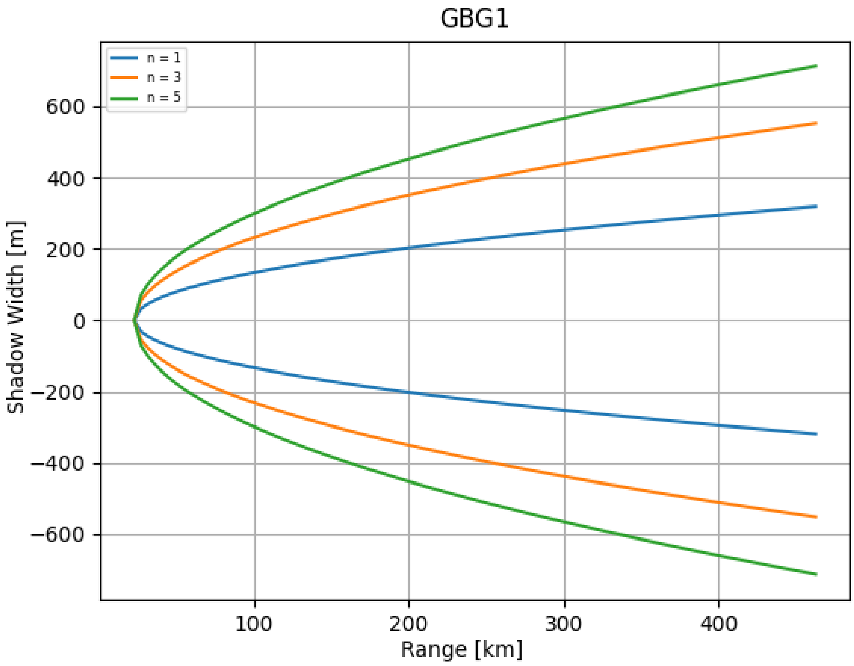

Figure 4.4: Actual representation of the shadow width for different Fresnel zones

Partial conclusion: We notice that the wind turbine under test generates an additional shadow width zone.

In reality, the shadow zone will not extend until the full instrumental range but will only occur the first kilometers behind a turbine.

Due to the weaker signal coming from forward scattering of the turbine only a reduction in power will be measured in the shadow width zones, not a complete loss of signal. This effect will be the strongest in the first Fresnel zone (n = 1) and will be almost undetectable in the 3rd relevant Fresnel zone (n = 5).

Raised threshold above and around the turbine

The possible large reflections of the wind turbine raise the detector threshold of the radar, which lowers the probability of detection of a target. The size of the region depends on the CFAR algorithm installed, as specified in section 2.2.

Given the size of a range cell, we calculate that a wind turbine can potentially influence the radar threshold ±788.4 meters from its position. Combined with the beam width and distance to the turbine under test we obtain the following impacted zones, see figure D.6.

Scenario 1: Licensed Skalden Wind Turbines (8)

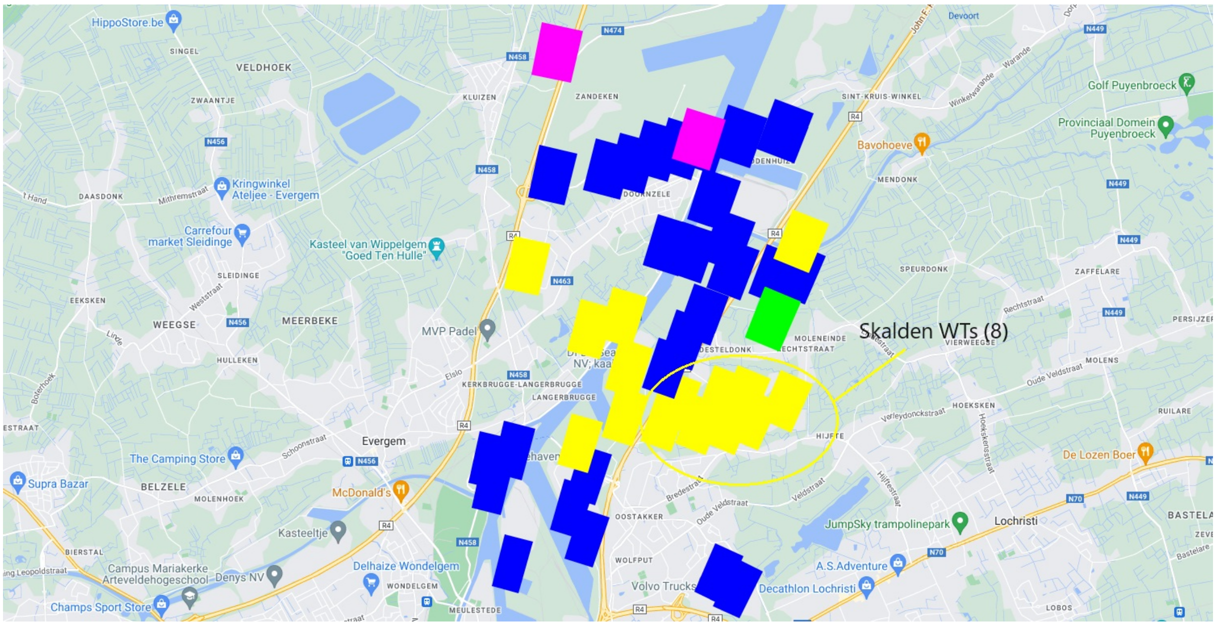

Figure 4.5: Schematic representation of the impacted S723 CFAR region.

The blue cells represent the raised threshold zone of existing turbines, the yellow cells the licensed turbines and the cells in magenta the turbines in application. The raised threshold zone of the turbines under test is represented by the green cells. If we compare turbines in other permission processes (blue, yellow and magenta) with the turbine under test (green area) we can see a netto increase of the CFAR impacted region, the calculations are given in table 4.4.

The raised threshold zone of the turbine under test has overlapping with a severe raised threshold zone of turbines in other permission processes, for this a cumulative effect of **1dB** has been taken into account.

Area before	Area after	Difference	Difference
13.8km^2	14.17km^2	0.37km^2	2.68%

Table 4.4: CFAR Area increase - Scenario 1

Scenario 2: Applicated Skalden Wind Turbines (4)

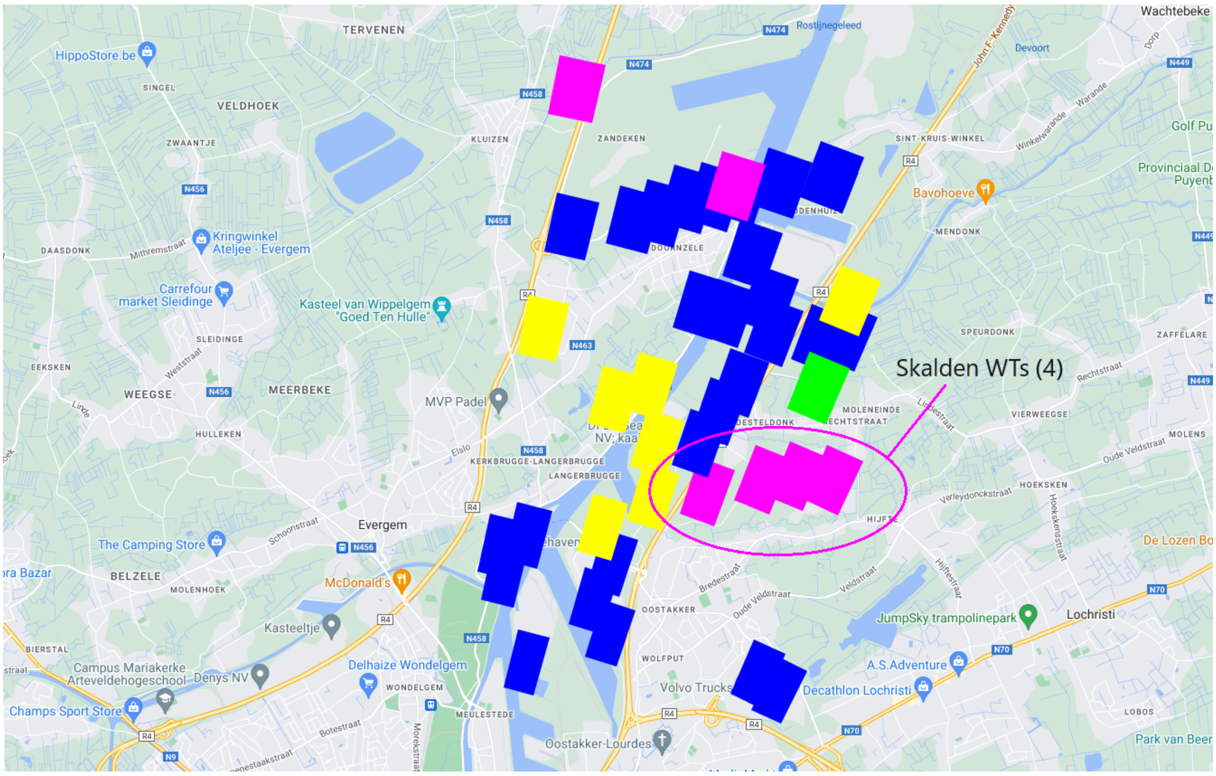

Figure 4.6: Schematic representation of the impacted S723 CFAR region.

If we compare turbines in other permission processes (blue, yellow and magenta) with the turbine under test (green area) we can see a netto increase of the CFAR impacted region, the calculations are given in table 4.5.

The raised threshold zone of the turbine under test has overlapping with a severe raised threshold zone of turbines in other permission processes, for this a cumulative effect of **1dB** has been taken into account.

Area before	Area after	Difference	Difference
$14.53km^2$	$14.9km^2$	$0.37km^2$	2.55%

Table 4.5: CFAR Area increase - Scenario 2

Monostatic RCS of the turbine under test [L-band]

The results of the turbine RCS calculations are displayed below, figure 4.7.
Fore more information on the monostatic RCS calculation of a wind turbine, see section D.1.

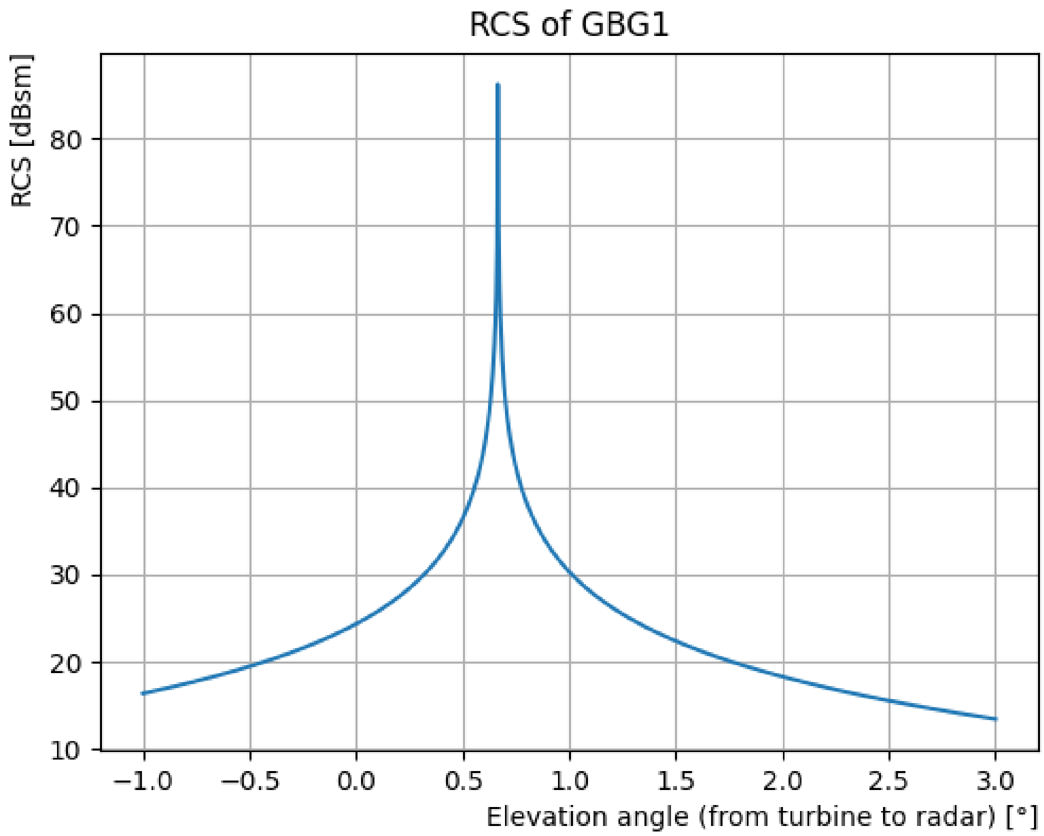

Figure 4.7: Monostatic RCS of the turbine under test at different elevation angles

Turbine	Elevation Angle [°]	RCS S-band [dBsm]
GBG1	0.026	24.7

Table 4.6: Overview monostatic RCS simulation of the turbine under test

A worst case average value of 24.7dBsm for the mast can be taken into account. This RCS value represents the ideal scenario in which no fluctuation losses occur (also known as Swerling). In reality the RCS will vary in strength. When adding the RCS of the rotor (15dBsm), the complete turbine monostatic RCS is about 25.1dBsm.

Taking into account the cumulative effect of 1dB (section 4.1.1), the total impact on the CFAR algorithm is about **26.1dBsm**.

To present the case for the S723 Semmerzake radar we display the results for a WT RCS of 20, 25 and 30dBsm. For the complete results, see annex B.

WT	Beam	Reference	500m	1000m	1500m	2000m	3000m	4000m
GBG1	1.0	-77.0[dBw]	-70.3	-76.8	-85.9	-92.6	-95.2	-109.4
GBG1	2.0	-84.0[dBw]	-72.4	-69.0	-72.0	-80.4	-94.2	-98.9
GBG1	3.0	-97.0[dBw]	-85.4	-77.2	-70.6	-69.7	-84.9	-94.4
GBG1	4.0	-104.0[dBw]	-93.0	-89.3	-82.6	-74.3	-71.2	-88.5
GBG1	5.0	-117.0[dBw]	-109.4	-96.5	-92.0	-86.8	-71.3	-72.8
GBG1	6.0	-117.0[dBw]	-109.4	-109.4	-109.4	-102.6	-88.8	-74.1
GBG1	7.0	-117.0[dBw]	-109.4	-109.4	-109.4	-109.4	-109.4	-90.6
GBG1	8.0	-117.0[dBw]	-109.4	-109.4	-109.4	-109.4	-109.4	-109.4

Table 4.7: Detection of a 0 dBsm target at different altitudes (RCS$_{WT}$= 20dBsm)

WT	Beam	Reference	500m	1000m	1500m	2000m	3000m	4000m
GBG1	1.0	-72.0[dBw]	-70.3	-76.8	-85.9	-92.6	-95.2	-109.4
GBG1	2.0	-79.0[dBw]	-72.4	-69.0	-72.0	-80.4	-94.2	-98.9
GBG1	3.0	-92.0[dBw]	-85.4	-77.2	-70.6	-69.7	-84.9	-94.4
GBG1	4.0	-99.0[dBw]	-93.0	-89.3	-82.6	-74.3	-71.2	-88.5
GBG1	5.0	-112.0[dBw]	-109.4	-96.5	-92.0	-86.8	-71.3	-72.8
GBG1	6.0	-112.0[dBw]	-109.4	-109.4	-109.4	-102.6	-88.8	-74.1
GBG1	7.0	-112.0[dBw]	-109.4	-109.4	-109.4	-109.4	-109.4	-90.6
GBG1	8.0	-112.0[dBw]	-109.4	-109.4	-109.4	-109.4	-109.4	-109.4

Table 4.8: Detection of a 0 dBsm target at different altitudes (RCS$_{WT}$= 25dBsm)

WT	Beam	Reference	500m	1000m	1500m	2000m	3000m	4000m
GBG1	1.0	-67.0[dBw]	-70.3	-76.8	-85.9	-92.6	-95.2	-109.4
GBG1	2.0	-74.0[dBw]	-72.4	-69.0	-72.0	-80.4	-94.2	-98.9
GBG1	3.0	-87.0[dBw]	-85.4	-77.2	-70.6	-69.7	-84.9	-94.4
GBG1	4.0	-94.0[dBw]	-93.0	-89.3	-82.6	-74.3	-71.2	-88.5
GBG1	5.0	-107.0[dBw]	-109.4	-96.5	-92.0	-86.8	-71.3	-72.8
GBG1	6.0	-107.0[dBw]	-109.4	-109.4	-109.4	-102.6	-88.8	-74.1
GBG1	7.0	-107.0[dBw]	-109.4	-109.4	-109.4	-109.4	-109.4	-90.6
GBG1	8.0	-107.0[dBw]	-109.4	-109.4	-109.4	-109.4	-109.4	-109.4

Table 4.9: Detection of a 0 dBsm target at different altitudes (RCS$_{WT}$= 30dBsm)

The 'Reference' column in the tables above state the value of the reflected power coming from a turbine after applying all mitigations (and CFAR) present in the radar. The overflying targets can only be detected if the returned power is larger than this reference value, in this case the cell will be green, otherwise red.

The simulated overflying target with a RCS of 0dBsm will be visible between altitudes:

- 500-4000m AMSL for a turbine RCS of 20
- 500-4000m AMSL for a turbine RCS of 25
- 500-4000m AMSL for a turbine RCS of 30

The expected RCS impact on the CFAR algorithm is about **26.1dBsm**. This is the worst case scenario with cumulative effects from the turbine under test.

The Semmerzake radar has adaptive/automatic VCC installed to compensate for wind turbine reflections.

For a complete overview of the returned power of the aircraft under test for different turbine RCS values, see appendix B.

4.1.2 PSR false target reports

Modern surveillance radars are equipped with multiple mechanisms to obtain detections of flying targets only, including pulse-doppler processing, beamforming and antenna patterns, and target trackers. To suppress reflections at non-moving objects (stator), adaptive cluttermaps are maintained within each doppler bin.

A flying target will be detected if its reflection exceeds the risen CFAR threshold in its range-azimuth cell.

Since the RCS of the turbine under test will vary over time (even within a single rotation), false targets will be present if no mitigations are applied.

4.1.3 PSR processing overload

The extra video processing as a result of the wind turbine under test is negligible in comparison with the radar technology used.

4.2 Practical analysis

For the practical analysis, the impact of the surrounding turbines is analysed which consists of an analysis of the video data that is processed by the extraction chain of the Semmerzake radar. In this analysis, the default signal processing chain is simulated to assess the impact on the clutter map (subsection 4.2.1) and the probability of detection (subsection 4.2.2) of the Semmerzake radar. The position of the turbine under test relative to the Semmerzake radar can be seen below in table 4.10.

Turbine	Range [NM]	Azimuth [°]
GBG1	12.06	22.21

Table 4.10: Turbine under test relative to Semmerzake radar

4.2.1 Clutter investigation in the area under test

To estimate the importance of a turbine in this region, the effects of wind turbines at similar distances to the radar are inspected on the radar clutter map. For the clutter investigation, 3 of the 8 Semmerzake radar beams have been analysed: beam 1, 4 and 8. The clutter maps of the 3 beams can be visualised in figures 4.8 and 4.9 The zone of the turbine under test is visualised with the yellow marker. The clutter legend can be found in annex C.1.

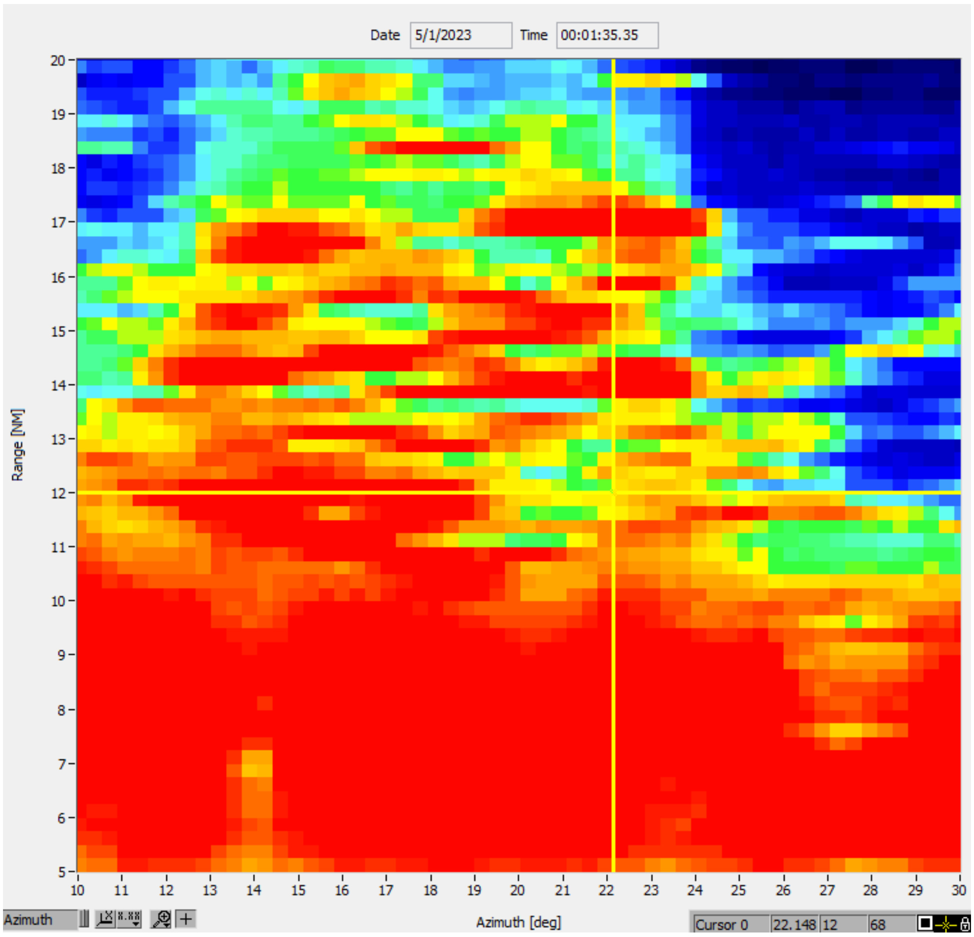

Figure 4.8: Clutter map of the Semmerzake radar [Beam 1]

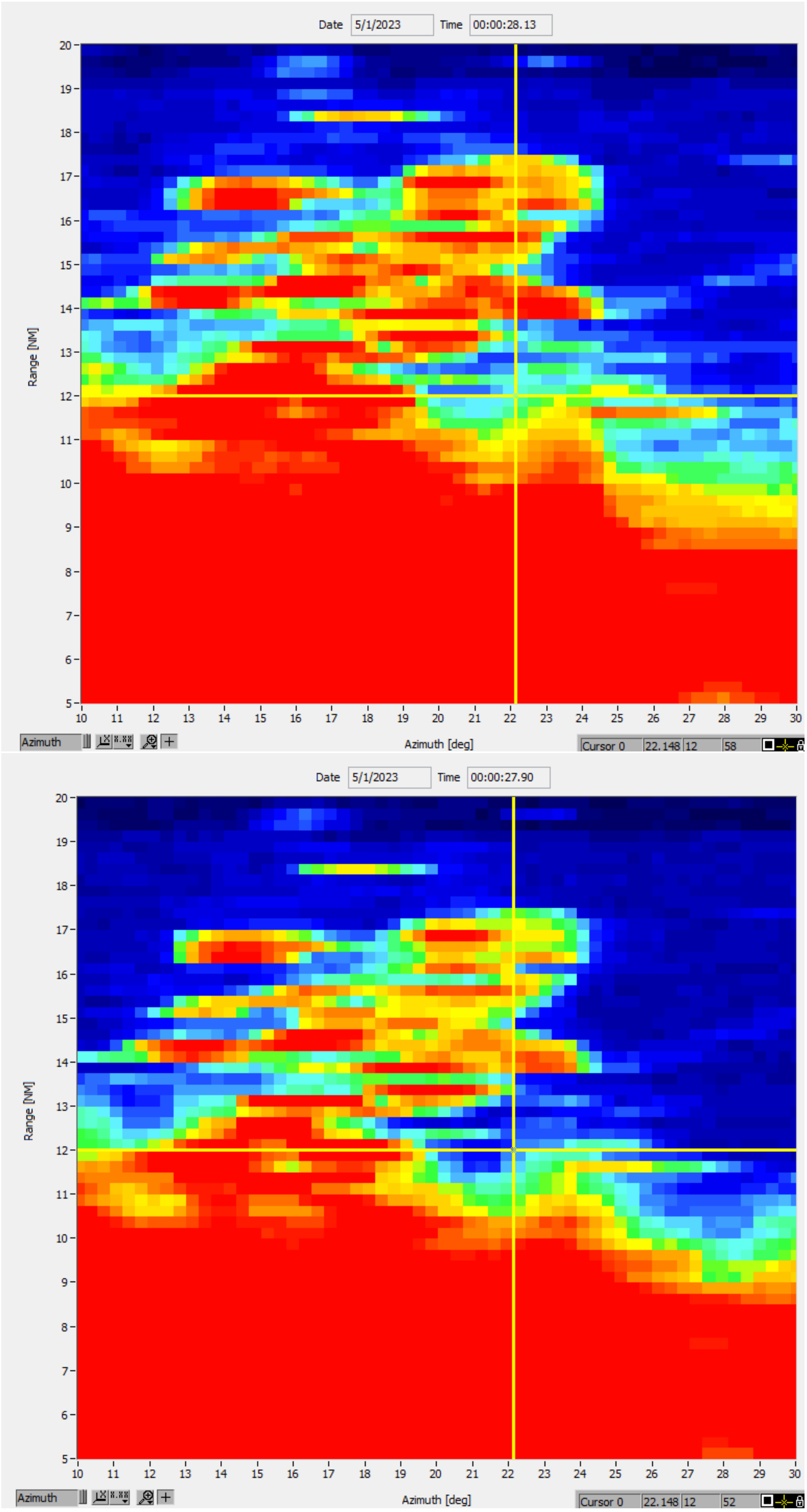

Figure 4.9: Clutter map of the Semmerzake radar [Beam 4 (up) - Beam 8 (down)]

The turbine under test is located in a clutter zone, due to this, no new clutter signatures are expected after the installation of the project. The presence of the new turbine may lead to intensification or widening of clutter in the zone of interest.

The S723 Semmerzake radar features adaptive/automatic VCC to mitigate influences of wind turbines on the clutter environment, however the effect of VCC might be insignificant due to the turbine under test already being situated in an intense clutter zone.

4.2.2 Visualization of the probability of detection

In figure 4.10 the marker is placed in the vicinity of the turbine under test, which shows the current Pd in the region. This is from extracted radar data (EDR) from 23 July 2023. The parameters of the RCM can be found in annex C.1.

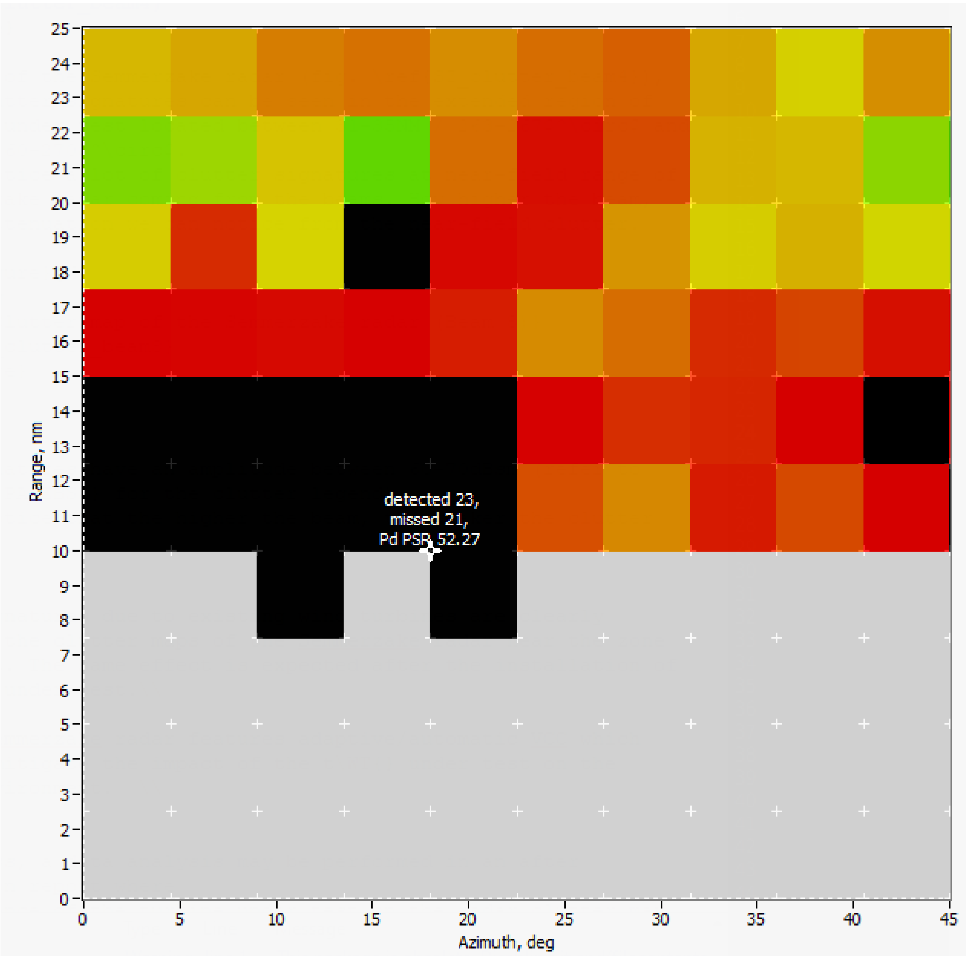

Figure 4.10: Visualisation of the Pd in the vicinity of the turbine under test (12 hours of data)

The Pd in this region is **52.27%** with 23 detections and 21 misses. This is very low but can be expected considering the intense and large clutter in this area (refer to the clutter map figures: 4.8 and 4.9).

5. Conclusion

5.1 Semmerzake Marconi S723

Shadow width and height effects will be present for the S723 Semmerzake radar which can impact the PSR Probability of detection in a small way due to the screening and interference of the turbine under test.

The shadow height will limit itself to the part of the turbine under test which is higher than the surrounding obstacles or that reach above the shadow zone of objects closer to the radar. In the case of the new turbine, the shadow height will increase with (**4158m**) or (**37%**) at full instrumental range. The shadow width zone caused by the new turbine will merge with the shadow zones generated by the surrounding obstacles.

The impact on the CFAR processing will be limited due to the fact that adaptive/automatic VCC is installed on the Semmerzake radar. The area of the CFAR impacted zone increases with 0.37km^2 or 2.55%. The raised threshold zone of the turbine has a minor overlap with a zone of the turbines in other permission processes which will cause a cumulative effect of about 1dB (section 4.1.1).

0dBsm/1m^2 simulated targets can be detected from very low altitudes [500m AMSL (RCS_{WT} $\leq$30dBsm)]. Higher RCS values will hardly reduce the visibility at the lower altitude ranges: a reflectivity of 35dBsm will make the smallest overflying targets visible as of 1500m AMSL. The average RCS value is simulated to be around **26.1dBsm**. Note that the RCS value for the simulated small target [0dBsm=1m^2] is far below those of classic airplanes and the most common combat aircrafts or helicopters.

No impact is expected on the detection performance.

No PSR false target reports or processing overload are to be expected.

General Conclusion: The installation of the **Gent** wind project on behalf of **Groep Blockmans Green** should not generate extra limitations on the Marconi S723 Long Range radar system. The consequences of wind turbines are mostly compensated by the automatic mitigations integrated in the Semmerzake radar (adaptive/automatic VCC). However, detection capabilities are already very limited in this area (Pd=52.27%).

It is recommended to investigate the clutter maps and detection performance after the installation of the project.

6. Samenvatting

Voor het project van **Projectgroep Blockmans Green , Gent** met de voorgestelde turbine (Tabel 6.1) werd een SEA uitgevoerd ten opzichte van de radar van Semmerzake om de invloed van deze turbine op de performantie van de vermelde radar te onderzoeken.

Turbine	**X**	**Y**	**Height**	**Hub Height**	**Rotor** ∅
GBG1	109668	201947	210m	129m	163m

Table 6.1: Turbine onder test

De afstanden tussen de radar systemen en de turbine zijn te vinden in Tabel 6.2. Deze tonen aan dat geen Detailed Engineering Assessment (DEA) noodzakelijk is.

Turbine	**Distance [NM]**	**Distance [km]**
GBG1	12.06	22.33

Table 6.2: Afstand tussen de turbine en de radar van Semmerzake

Alle noodzakelijke aspecten werden in de studie bestudeerd:

- PSR probability of detection
- PSR false target reports
- PSR processing overload

6.1 Semmerzake

De nieuwe turbine genereert een bijkomende schaduwzone in zowel de horizontale als de verticale dimensie. Bij de maximale instrumentele afstand (265NM/474km) is dit verschil **4158m** of **37%** ten opzichte van de schaduwzone gegenereerd door het terrein. In de realiteit dient men nog rekening te houden met de golfeffecten, dit wordt niet beschreven in de algemene werkwijze voorgeschreven in het EUROCONTROL document. Door deze effecten zal de schaduwzone zich beperken tot de eerste kilometers achter de turbine, waarna het veld zich terug zal herstellen door constructieve interferentie van de gerefracteerde signalen.

De breedte van deze schaduwzones werd bepaald aan de hand van de verschillende Fresnelzones. Bij het maximale bereik van de radar zijn deze ongeveer 600 m breed (voor de derde Fresnelzone). Opnieuw is de opmerking van hierboven geldig, doordat het veld zich zal herstellen enkele kilometers achter de turbine zal dit effect beperkt blijven.

Door de grote RCS waarden die windturbines hebben kan de detectie drempel van de radar in de buurt van turbines verhogen, waardoor vliegtuigen in deze zone minder goed gedetecteerd kunnen worden. Voor de radar van Semmerzake gaat het om een zone van ±788.4m voor en na elke turbine met een breedte die gelijk is aan de openingshoek van de radar (main beam 3dB hoek). De impact op de CFAR zone rond de nieuwe turbine zal gelimiteerd zijn doordat de Semmerzake radar adaptieve/automatische VCC integreert.

Wanneer de reflecties van de turbine 30dBsm of minder bedraagt, zullen kleine toestellen (0dBsm) vanaf 500m altijd gedetecteerd worden, bij hogere waarden zal de visibiliteit van kleine toestellen verminderen. De verwachte RCS impact (met cumulatief effect) bedraagt **26.1dBsm**, rekening houdend met de mast van de turbine die in realiteit niet gezien worden door de radar.

Moderne surveillance radars beschikken over meerdere mechanismen om bewegende voorwerpen te onderscheiden van stilstaande (e.g. MTI/MTD). Hierdoor worden de reflecties van de stator volledig weggefilterd. Om andere vormen van ongewenste target reports tegen te gaan zijn meerdere systemen actief waarbij adaptieve cluttermaps binnen elke doppler bin bijgehouden worden. Slechts wanneer reflecties door alle filters geraken, zullen deze beschouwd worden als target.

De bijkomende verwerking van video signalen door toevoeging van de wind turbine die bestudeerd werden is zeer beperkt vergeleken met de gebruikte technologie.

Alle berekeningen, simulaties en de praktische analyse tonen aan dat de performantie van de radar van Semmerzake bijna verwaarloosbaar zal zijn door de turbine beschouwd in deze studie.

Bibliography

[1] Frank BRENNER, *EUROCONTROL Guidelines for Assessing the Potential Impact on Wind turbine on Surveillance Sensors*, GUID-130, Edition 1.2, Sept 2014.

[2] Merrill Skolnik, *RADAR handbook*, Third edition

[3] Marcel Vanuytven, *Octrooi WO 2010/037770*, 08/04/2010

[4] Gavin J Poupart, *Wind farms impact on radar aviation - Final report*, DTI PUB URN 03/1294, September 2003

[5] Intersoft Electronics, Next Generation Signal Processor (NGSP), `https://intersoft-electronics.com/technology_components_ngsp.html`, 2021

[6] U.S. Geological Survey, `https://dds.cr.usgs.gov`, August 2020

[7] Vincent De Smet *RE: Engineering studie BAF* 13/03/2018

[8] `https://www.geopunt.be/?service=https%3A%2F%2Fwww.mercator.vlaanderen.be%2Fraadpleegdienstenmercatorpubliek%2Fows%3Flayers%3Der%3Aer_windturb_st_aangevr`

[9] ScientificWorldJournal, *Simplified Formulae for the Estimation of Offshore Wind Turbines Clutter on Marine Radars.*, March 2017

[10] Thales Air Systems, *Radar Innovation & the development of Wind Energy.* Conference "Energie éolienne et innovation", MEDDTL, Paris, 5 July 2011

[11] Natural Resources Canada, *Radar Image Distortion*, 2015-11-20

Appendices

A. Turbines in the vicinity

Scenario 1 (Licensed Skalden Wind Turbines (8))

Turbine	Lambert X	Lambert Y	Height	Status
$WT06_AB$	108130	203055	193m	Operational
$ASPWT2$	106491	205925	180m	Application
$KDIIWT5$	106409	204106	152m	Operational
$MXWT1$	108810	203720	152m	Operational
WT_01	105761	198338	149m	Operational
$SkaldenWTB3$	109243	200802	200m	Licensed
$SkaldenWTB2$	109370	200454	200m	Licensed
$SkaldenWTB4$	109863	200718	200m	Licensed
$SkaldenWT3$	108574	200383	200m	Licensed
$SkaldenWT2$	108234	200732	200m	Licensed
$SkaldenWTB1$	109011	200387	200m	Licensed
$SkaldenWT4$	108897	200805	200m	Licensed
$SkaldenWT1$	108052	200436	200m	Licensed
$WT3_RH_E$	109082	202694	200m	Operational
$WT2_RH_E$	109022	203110	200m	Operational
$WT1_RH_E$	108481	202945	200m	Operational
WT_MER	107460	200514	250m	Licensed
SE_WT3	105473	199504	193.4m	Operational
$GC\&TWT3$	108087	201225	150m	Operational
SE_WT2	105432	199874	193.4m	Operational
$GC\&TWT2$	108630	202015	150m	Operational
SE_WT1	105792	200020	193.4m	Operational
$GC\&TWT1$	108356	201641	150m	Operational
$MVZuidWT2$	110052	202627	200m	Operational
$VTWT1$	108839	198162	139m	Operational
$VCWT3$	106910	199646	146m	Operational
$MVZuidWT1$	109715	202591	200m	Operational
$MV2$	110103	203099	238.5m	Licensed
$VTWT2$	109121	197945	139m	Operational
$VCWT2$	106660	199146	146m	Operational
$VCWT1$	106876	198711	146m	Operational
$WT01-VLS$	107525	201227	180m	Licensed
$WT-ATS$	107438	201986	230m	Licensed
$WT01_Nest$	106019	202761	198m	Licensed
$CBRGent$	109199	204660	240m	Operational
$KDWT5$	107240	204192	133.5m	Operational
$KDWT2$	108320	204485	133.5m	Operational
$KDWT4$	107596	204270	133.5m	Operational
$KDWT3$	107958	204461	133.5m	Operational

Turbine	Lambert X	Lambert Y	Height	Status
$KDWT1$	108672	204558	133.5m	Operational
$WTSH$	106791	200122	200m	Licensed
$WT07_Sadaci$	106963	201810	198m	Licensed
$WT05_S$	109878	204734	200m	Operational
KD_R04	108589	204627	250m	Application

Table A.1: Turbines in the vicinity (10km)

Scenario 2 (Applicated Skalden Wind Turbines (4))

Turbine	Lambert X	Lambert Y	Height	Status
$WT06_AB$	108130	203055	193m	Operational
$ASPWT2$	106491	205925	180m	Application
$KDIIWT5$	106409	204106	152m	Operational
$MXWT1$	108810	203720	152m	Operational
WT_01	105761	198338	149m	Operational
WTE_01	108182	200582	250m	Application
WTE_02	108927	200735	250m	Application
WTE_03	109379	200774	250m	Application
WTE_04	109860	200720	250m	Application
$WT3_RH_E$	109082	202694	200m	Operational
$WT2_RH_E$	109022	203110	200m	Operational
$WT1_RH_E$	108481	202945	200m	Operational
WT_MER	107460	200514	250m	Licensed
SE_WT3	105473	199504	193.4m	Operational
$GC\&TWT3$	108087	201225	150m	Operational
SE_WT2	105432	199874	193.4m	Operational
$GC\&TWT2$	108630	202015	150m	Operational
SE_WT1	105792	200020	193.4m	Operational
$GC\&TWT1$	108356	201641	150m	Operational
$MVZuidWT2$	110052	202627	200m	Operational
$VTWT1$	108839	198162	139m	Operational
$VCWT3$	106910	199646	146m	Operational
$MVZuidWT1$	109715	202591	200m	Operational
$MV2$	110103	203099	238.5m	Licensed
$VTWT2$	109121	197945	139m	Operational
$VCWT2$	106660	199146	146m	Operational
$VCWT1$	106876	198711	146m	Operational
$WT01 - VLS$	107525	201227	180m	Licensed
$WT - ATS$	107438	201986	230m	Licensed
$WT01_Nest$	106019	202761	198m	Licensed
$CBRGent$	109199	204660	240m	Operational
$KDWT5$	107240	204192	133.5m	Operational
$KDWT2$	108320	204485	133.5m	Operational

Turbine	**Lambert X**	**Lambert Y**	**Height**	**Status**
$KDWT4$	107596	204270	133.5m	Operational
$KDWT3$	107958	204461	133.5m	Operational
$KDWT1$	108672	204558	133.5m	Operational
$WTSH$	106791	200122	200m	Licensed
$WT07_Sadaci$	106963	201810	198m	Licensed
$WT05_S$	109878	204734	200m	Operational
KD_R04	108589	204627	250m	Application

Table A.2: Turbines in the vicinity (10km)

B. Impact on the CFAR

This chapter gives the estimated returned power of a reference target of 0dBsm and compares this to the incident power coming from the wind turbine after all of the data processing (CFAR, VCC, MTD, ...) This makes it possible to check from which altitudes a small aircraft can be detected.

B.1 Semmerzake

WT RCS 10 dBsm

WT	Beam	Threshold	500m	1000m	1500m	2000m	3000m	4000m
GBG1	1.0	-87.0[dBw]	-70.3	-76.8	-85.9	-92.6	-95.2	-109.4
GBG1	2.0	-94.0[dBw]	-72.4	-69.0	-72.0	-80.4	-94.2	-98.9
GBG1	3.0	-107.0[dBw]	-85.4	-77.2	-70.6	-69.7	-84.9	-94.4
GBG1	4.0	-114.0[dBw]	-93.0	-89.3	-82.6	-74.3	-71.2	-88.5
GBG1	5.0	-127.0[dBw]	-109.4	-96.5	-92.0	-86.8	-71.3	-72.8
GBG1	6.0	-127.0[dBw]	-109.4	-109.4	-109.4	-102.6	-88.8	-74.1
GBG1	7.0	-127.0[dBw]	-109.4	-109.4	-109.4	-109.4	-109.4	-90.6
GBG1	8.0	-127.0[dBw]	-109.4	-109.4	-109.4	-109.4	-109.4	-109.4

WT RCS 15 dBsm

WT	Beam	Threshold	500m	1000m	1500m	2000m	3000m	4000m
GBG1	1.0	-82.0[dBw]	-70.3	-76.8	-85.9	-92.6	-95.2	-109.4
GBG1	2.0	-89.0[dBw]	-72.4	-69.0	-72.0	-80.4	-94.2	-98.9
GBG1	3.0	-102.0[dBw]	-85.4	-77.2	-70.6	-69.7	-84.9	-94.4
GBG1	4.0	-109.0[dBw]	-93.0	-89.3	-82.6	-74.3	-71.2	-88.5
GBG1	5.0	-122.0[dBw]	-109.4	-96.5	-92.0	-86.8	-71.3	-72.8
GBG1	6.0	-122.0[dBw]	-109.4	-109.4	-109.4	-102.6	-88.8	-74.1
GBG1	7.0	-122.0[dBw]	-109.4	-109.4	-109.4	-109.4	-109.4	-90.6
GBG1	8.0	-122.0[dBw]	-109.4	-109.4	-109.4	-109.4	-109.4	-109.4

WT RCS 20 dBsm

WT	Beam	Threshold	500m	1000m	1500m	2000m	3000m	4000m
GBG1	1.0	-77.0[dBw]	-70.3	-76.8	-85.9	-92.6	-95.2	-109.4
GBG1	2.0	-84.0[dBw]	-72.4	-69.0	-72.0	-80.4	-94.2	-98.9
GBG1	3.0	-97.0[dBw]	-85.4	-77.2	-70.6	-69.7	-84.9	-94.4
GBG1	4.0	-104.0[dBw]	-93.0	-89.3	-82.6	-74.3	-71.2	-88.5

WT	Beam	Threshold	500m	1000m	1500m	2000m	3000m	4000m
GBG1	5.0	-117.0[dBw]	-109.4	-96.5	-92.0	-86.8	-71.3	-72.8
GBG1	6.0	-117.0[dBw]	-109.4	-109.4	-109.4	-102.6	-88.8	-74.1
GBG1	7.0	-117.0[dBw]	-109.4	-109.4	-109.4	-109.4	-109.4	-90.6
GBG1	8.0	-117.0[dBw]	-109.4	-109.4	-109.4	-109.4	-109.4	-109.4

WT RCS 25 dBsm

WT	Beam	Threshold	500m	1000m	1500m	2000m	3000m	4000m
GBG1	1.0	-72.0[dBw]	-70.3	-76.8	-85.9	-92.6	-95.2	-109.4
GBG1	2.0	-79.0[dBw]	-72.4	-69.0	-72.0	-80.4	-94.2	-98.9
GBG1	3.0	-92.0[dBw]	-85.4	-77.2	-70.6	-69.7	-84.9	-94.4
GBG1	4.0	-99.0[dBw]	-93.0	-89.3	-82.6	-74.3	-71.2	-88.5
GBG1	5.0	-112.0[dBw]	-109.4	-96.5	-92.0	-86.8	-71.3	-72.8
GBG1	6.0	-112.0[dBw]	-109.4	-109.4	-109.4	-102.6	-88.8	-74.1
GBG1	7.0	-112.0[dBw]	-109.4	-109.4	-109.4	-109.4	-109.4	-90.6
GBG1	8.0	-112.0[dBw]	-109.4	-109.4	-109.4	-109.4	-109.4	-109.4

WT RCS 30 dBsm

WT	Beam	Threshold	500m	1000m	1500m	2000m	3000m	4000m
GBG1	1.0	-67.0[dBw]	-70.3	-76.8	-85.9	-92.6	-95.2	-109.4
GBG1	2.0	-74.0[dBw]	-72.4	-69.0	-72.0	-80.4	-94.2	-98.9
GBG1	3.0	-87.0[dBw]	-85.4	-77.2	-70.6	-69.7	-84.9	-94.4
GBG1	4.0	-94.0[dBw]	-93.0	-89.3	-82.6	-74.3	-71.2	-88.5
GBG1	5.0	-107.0[dBw]	-109.4	-96.5	-92.0	-86.8	-71.3	-72.8
GBG1	6.0	-107.0[dBw]	-109.4	-109.4	-109.4	-102.6	-88.8	-74.1
GBG1	7.0	-107.0[dBw]	-109.4	-109.4	-109.4	-109.4	-109.4	-90.6
GBG1	8.0	-107.0[dBw]	-109.4	-109.4	-109.4	-109.4	-109.4	-109.4

WT RCS 35 dBsm

WT	Beam	Threshold	500m	1000m	1500m	2000m	3000m	4000m
GBG1	1.0	-62.0[dBw]	-70.3	-76.8	-85.9	-92.6	-95.2	-109.4
GBG1	2.0	-69.0[dBw]	-72.4	-69.0	-72.0	-80.4	-94.2	-98.9
GBG1	3.0	-82.0[dBw]	-85.4	-77.2	-70.6	-69.7	-84.9	-94.4
GBG1	4.0	-89.0[dBw]	-93.0	-89.3	-82.6	-74.3	-71.2	-88.5
GBG1	5.0	-102.0[dBw]	-109.4	-96.5	-92.0	-86.8	-71.3	-72.8
GBG1	6.0	-102.0[dBw]	-109.4	-109.4	-109.4	-102.6	-88.8	-74.1
GBG1	7.0	-102.0[dBw]	-109.4	-109.4	-109.4	-109.4	-109.4	-90.6
GBG1	8.0	-102.0[dBw]	-109.4	-109.4	-109.4	-109.4	-109.4	-109.4

C. Parameters RCM

C.1 Semmerzake

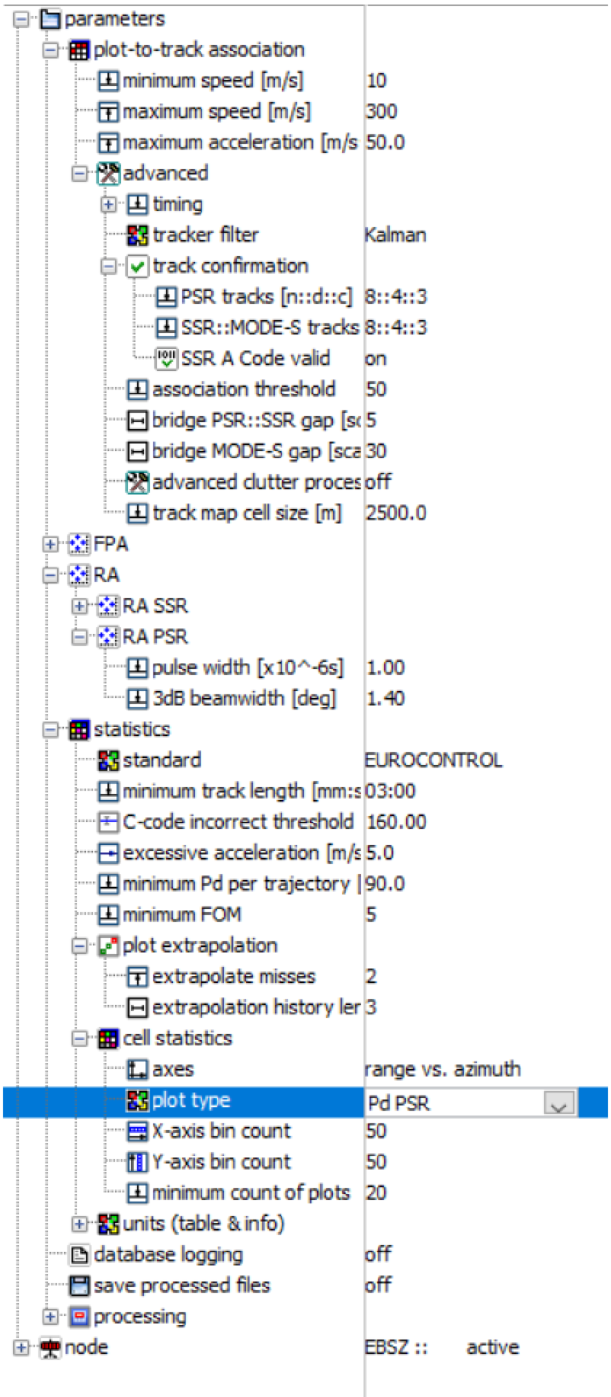

Figure C.1: Parameters RCM - Semmerzake

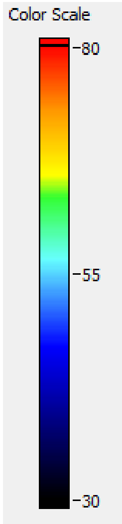

Figure C.2: Clutter map legend - Semmerzake

D. Information

This chapter gives a more verbose explanation of requirements, methodologies and concepts recurring in the simple engineering assessment to give the reader insight on the evaluation of the analysis's, calculations, simulations and conclusions.

D.1 PSR Probability of detection

The Eurocontrol Primary Surveillance Radar (PSR) probability of detection requirement sets a stringent standard for radar systems employed in air traffic control. It stipulates the minimum acceptable probability that the radar system must successfully detect and track an aircraft within its coverage area. This requirement is fundamental to ensuring the safety and effectiveness of air traffic management operations. Adherence to the specified probability of detection ensures that the radar system reliably detects and tracks aircraft, allowing for accurate positioning and facilitating safe air traffic separation. Meeting this requirement is essential in maintaining the high level of safety and efficiency expected in modern aviation operations. Therefore it is crucial to monitor the deployment of wind farms in the environment. These large obstacles can influence the sensitivity of radar systems and interfere with their detection capabilities.

Radar Shadow

Radar shadow occurs when the radar beam is not able to illuminate the ground surface. This phenomena occurs in the down range dimension (i.e. towards the far range), behind vertical features or slopes with steep sides [11]. If the tip height of a turbine is larger than the radar shadow, it is seen by the radar system. If the radar shadow exceeds the hub height, only the rotor is seen by the radar.

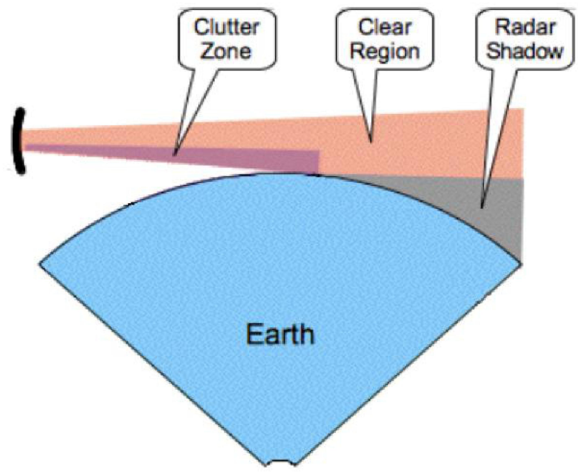

Figure D.1: Visualisation of the radar shadow region

Shadow regions behind a wind turbine

Wind turbines generates additional shadow zones in the vertical and horizontal dimension. Shadow zones in radar refer to areas where the electromagnetic field strength is weaker due to obstacles or terrain features blocking or scattering the radar waves. This can occur when the radar beam encounters objects such as buildings, mountains, or other structures that obstruct its path. As a result, the radar may not be able to fully illuminate or receive returns from the shadowed area, leading to a weaker electromagnetic field in that region.

Figure D.2: Visualisation of Shadow Regions behind wind turbines

The effect of shadow regions are caused by destructive interference between the radar signal and the forward scattered signal coming from wind turbines. The effect of these regions are significant until a few kilometers after a turbine and these regions will not extend until the maximum instrumented range of a radar.
When a wind turbine lies directly between a radar, the strength of the signal reaching the receiver is weaker due to the waves being refracted and bent. For a radar system, this is the case for every obstacle that is within its line of sight.

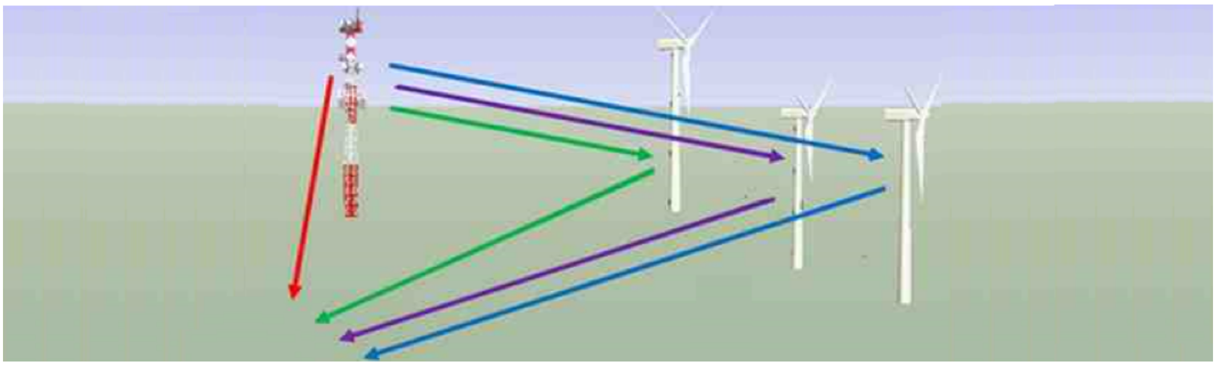

Figure D.3: Wave refraction due to wind turbines

The shadow regions gives an indication of the severity of this effect. The closer the turbine to the radar system, the bigger the expected impact. These calculations gives us the worst case scenario, in reality the shadow effects will be much smaller due to building obstructions and specific wave effects. For the calculations we took into account the 4/3 earth model.

Shadow Height

First we look into the shadow height. In the analysis, we compare the shadow height of wind turbines with the shadow generated by the terrain (SRTM [6]), a schematic representation is given in figure D.4. The calculations are based on screening with an optical model for the propagation of the electromagnetic rays.

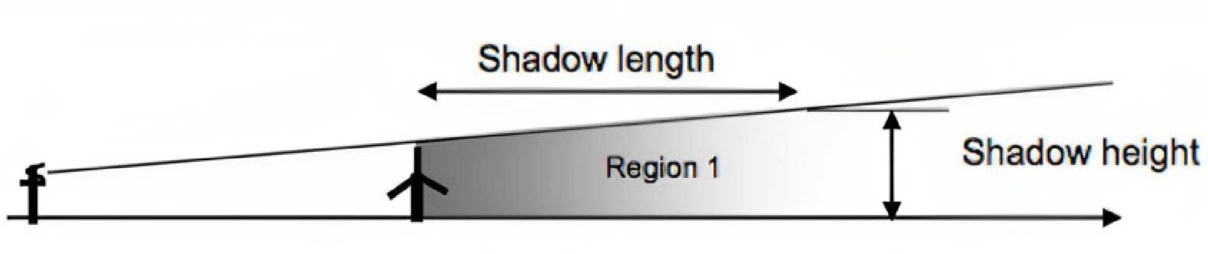

Figure D.4: Schematic representation of the shadow height region

Shadow Width

Similar to the shadow height we can calculate the shadow width which occurs due to the blocking of the radar signal in the azimuthal plane. The "signal blocking" is caused by destructive interference behind a wind turbine due to forward scattering effects.

The shadow width depends on the addition of the signal in phase and anti-phase. We calculate this for the three first *Fresnel zones* where destructive interference occurs (n = 1, 3 or 5).
Due to large differences in intensity between the forward scatter reflected of wind turbines and direct waves of the radar, this effect will only be noticeable close to wind turbines. This effect will be the most significant in the first Fresnel zone (n = 1) and will be almost undetectable in the 3rd relevant Fresnel zone (n = 5).

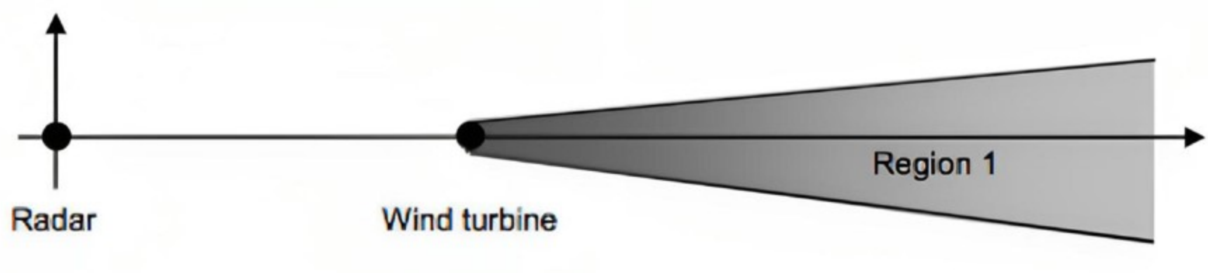

Figure D.5: Schematic representation of the shadow height region

Constant False Alarm Rate

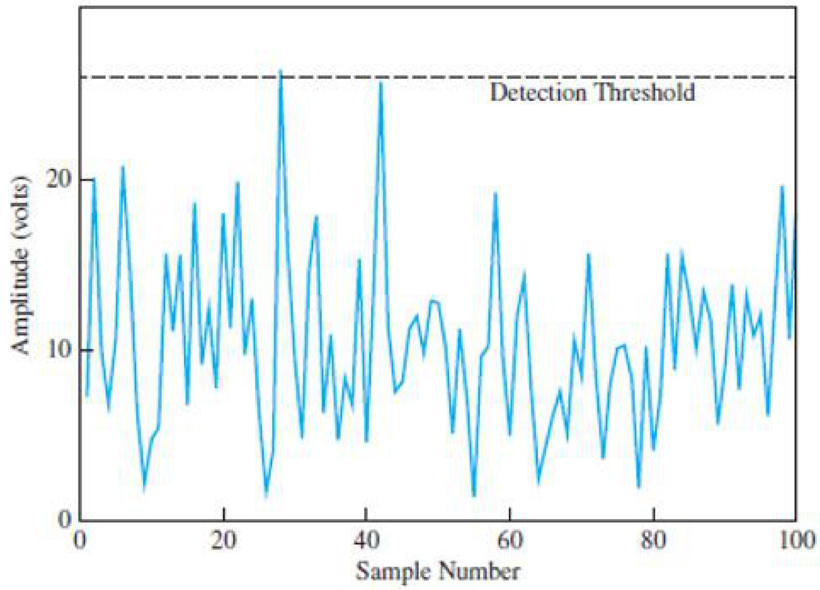

Figure D.6: Constant False Alarm Rate signal representation

The possible large reflections of wind turbines raise the detector threshold of radar systems, which lowers the detection performance and promote the detection of undesired targets. The detection algorithm implemented in the BAF radar systems is Constant False Alarm Rate (CFAR). This signal processing technique automatically adapts the threshold for target detection in the presence of varying levels of clutter and noise. It ensures that the probability of false alarms remains constant across different clutter environments. This detection technique improves the SNR ratio which makes it easier to distinguish targets from noise. CFAR is a critical technique for maintaining a constant false alarm rate in radar systems. It can be applied to each range-azimuth cell, which are determined based on the CFAR algorithm installed, desired range and azimuth resolutions. This ensures effective target detection in varying clutter environments.

Given the size of a range cell, we calculate that a wind turbine can potentially influence a radar threshold until a certain distance from its position. Combined with the radar beam width and distance to the turbines we calculate the impacted zones for the turbine under test and the existing/operational turbines. Depending on the number of impacted zones which overlaps and the degree of the overlapping, the reflections of the range-azimuth cell in the region of the wind project will be more intense. This additive effect will raise the detection threshold of a cell.

Monostatic RCS calculation of a wind turbine

To give an idea about the expected Radar Cross Section (RCS) of a wind turbine we perform a simplified RCS calculation. In this calculation we only take into account parts of the wind turbine which are visible for the radar system. As detailed simulations have shown, the turbine mast is the dominant contributor to the monostatic RCS, regardless of the orientation of the rotor [9].

The masts are simulated as the frustum of a cone and we calculate their monostatic RCS in relation to the different relevant EM incident angles.

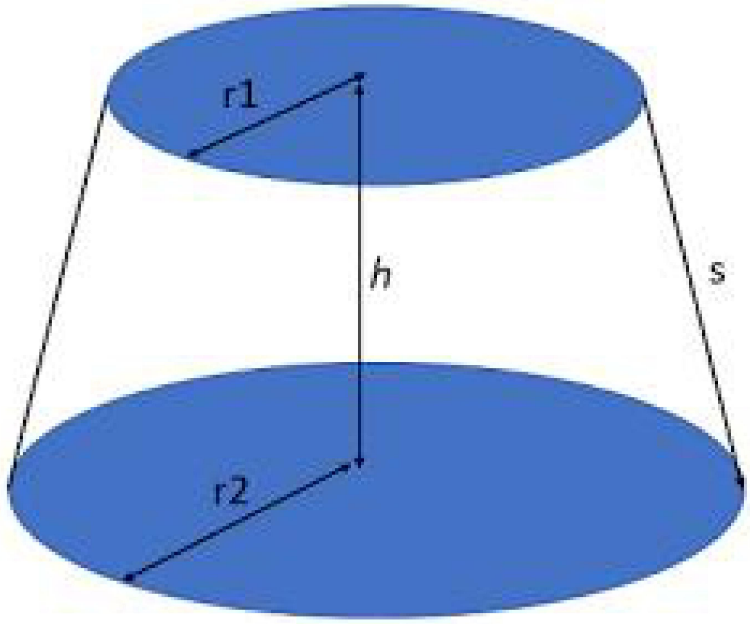

Figure D.7: Properties of the frustum of a cone

After calculating the monostatic RCS, we add a worst case value of 15dBsm for the RCS of the rotor and the CFAR cumulative effect to obtain the complete turbine monostatic RCS. This represents the worst case RCS impact on the CFAR algorithm. The calculated monostatic RCS value represents the ideal scenario in which no fluctuation losses occur (also known as Swerling). In reality the RCS will vary in strength.

As most neighbouring Belgian radars prone to the environmental influence of proposed wind turbines do not integrate automatic mitigations, the impact on the CFAR is generally considerable.

Representation of the CFAR test setup

For the RCS of the turbine under test different values have been used. In real life this will also be the case, depending on the wind direction and blade speed of the turbines. Even within one complete blade revolution this RCS value can vary by a factor of 10,000. A simplified statistical overview is given in the table below, D.1 [4].

Monostatic RCS L-band			
Maximum	Mean	Median	Minimum
37 dBsm	27 dBsm	27 dBsm	0 dBsm

Table D.1: Stochastic representation of monostatic RCS turbines, L-band

For this study we analysed the impact on the raised threshold above and around the turbine for RCS values of 10, 15, 20, 25, 30 and 35dBsm to simulate all possible scenarios. Next we calculated the impact on a target right above the turbine (worst case) at different altitudes. The target size is simulated as 0 dBsm ($1m^2$).

If the reflected power of the target remains above the detection threshold, it can still be seen by the radar system. In these calculations we processed the impact of MTI/MTD and the beam pattern. A schematic overview of our test set-up can be seen below:

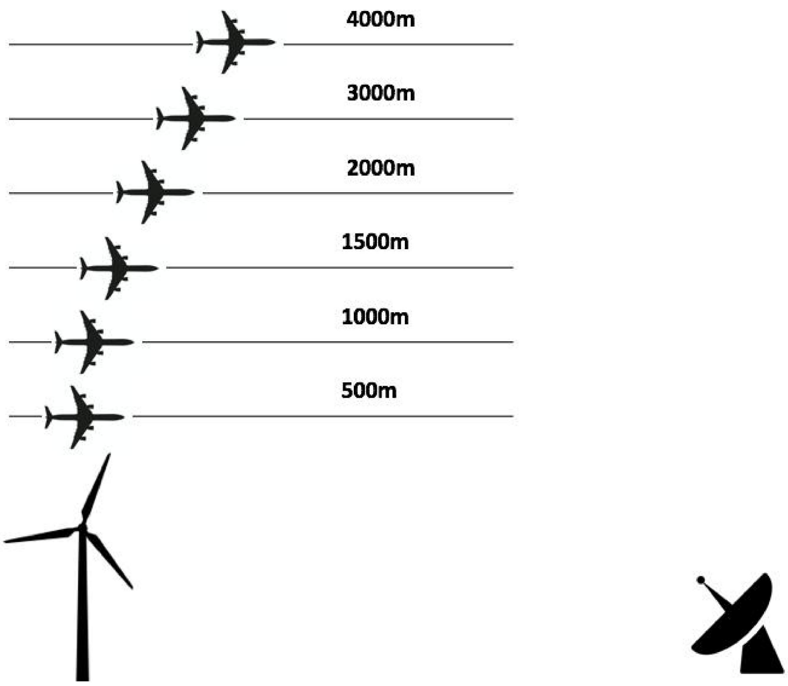

Figure D.8: Schematic representation of the CFAR test set-up

D.2 PSR false target reports

The Eurocontrol Primary Surveillance Radar (PSR) false target reports defined in the Eurocontrol document refer to spurious radar returns that are erroneously interpreted as legitimate aircraft tracks. Meeting the requirements outlined by Eurocontrol is essential for ensuring the accuracy and reliability of air traffic surveillance.

The Eurocontrol Primary Surveillance Radar (PSR) false target reports pertain to erroneous radar returns mistakenly identified as valid aircraft tracks. Eurocontrol has established stringent requirements to minimize the occurrence of these false reports. To meet these standards, radar systems must implement advanced signal processing techniques, such as clutter filtering and target discrimination algorithms. Additionally, rigorous testing and validation procedures are employed to verify the radar's performance in various operational scenarios. By adhering to Eurocontrol's specifications, radar systems can effectively mitigate false target reports, thereby enhancing the accuracy and integrity of air traffic surveillance.

D.3 PSR processing overload

The Eurocontrol Primary Surveillance Radar (PSR) processing overload requirements are critical standards that govern the capacity of radar systems to handle and process large volumes of data without experiencing performance degradation. Ensuring compliance with these requirements is essential for maintaining effective air traffic surveillance.

The Eurocontrol Primary Surveillance Radar (PSR) processing overload requirements define the radar system's capability to manage high data loads without compromising performance. Adherence to these standards is crucial for uninterrupted air traffic surveillance. To meet these requirements, radar systems employ sophisticated processing architectures and algorithms, including parallel processing techniques and optimized data handling protocols. Additionally, regular maintenance and system upgrades are conducted to ensure continued compliance with Eurocontrol specifications. By meeting the processing overload requirements, radar systems can sustain reliable and uninterrupted surveillance operations, even during periods of high data traffic.

E. Mitigations

Thanks to the implementation of Vertical Clutter Cancellation and Range Azimuth Gating mitigation techniques supported by NGSP (Next-Generation Signal Processing) based radar systems, wind farm and turbine projects become significantly more deployable. These advanced radar technologies effectively filter out unwanted clutter and noise, enabling precise detection and tracking of airborne targets. As a result, the interference caused by wind turbine reflections is greatly minimized, ensuring reliable and accurate radar performance. This enhanced capability boosts the viability and feasibility of wind energy projects, as it mitigates potential conflicts with nearby radar installations, thereby facilitating smoother regulatory approvals and project implementation.

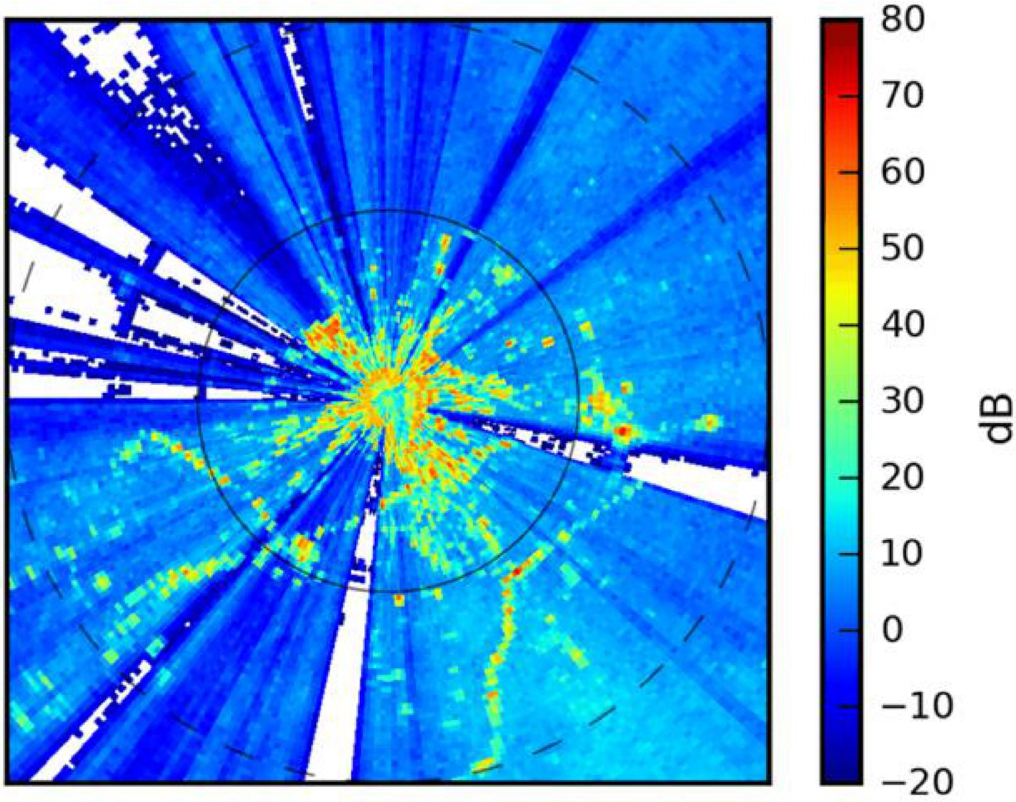

Figure E.1: Visualisation of radar ground clutter

E.1 Vertical Clutter Cancelation

Vertical Clutter Cancellation (VCC) is a sophisticated mitigation technique employed in radar systems to attenuate or even suppress the impact of ground clutter. Unwanted echoes can be a significant challenge to deal with in radar systems.

The purpose of VCC is to suppress or cancel out these clutter returns to enhance the radar's ability to detect targets.

Applying VCC to a radar system creates a notch in the radar beam pattern This notch represents a region where clutter returns are effectively canceled out or greatly reduced. This is particularly useful in situations where the clutter environment is well-defined and consistent.

VCC is particularly valuable in radar systems used in environments with challenging clutter conditions, such as near airports, wind farms, over bodies of water, or in regions with varied terrain.

By mitigating the effects of ground clutter, VCC allows the radar system to more accurately detect and track targets, especially in environments where ground clutter is a significant concern.

This is a powerful technique that significantly improves a radar system's ability to detect targets by effectively suppressing the impact of ground clutter. It's a crucial tool in environments where clutter interference can be a major obstacle to accurate target detection.

The effect of VCC on the radar signal processing can be simulated and presented in an **after installation report**. After the evaluation of this document, VCC tuning can be performed if necessary.

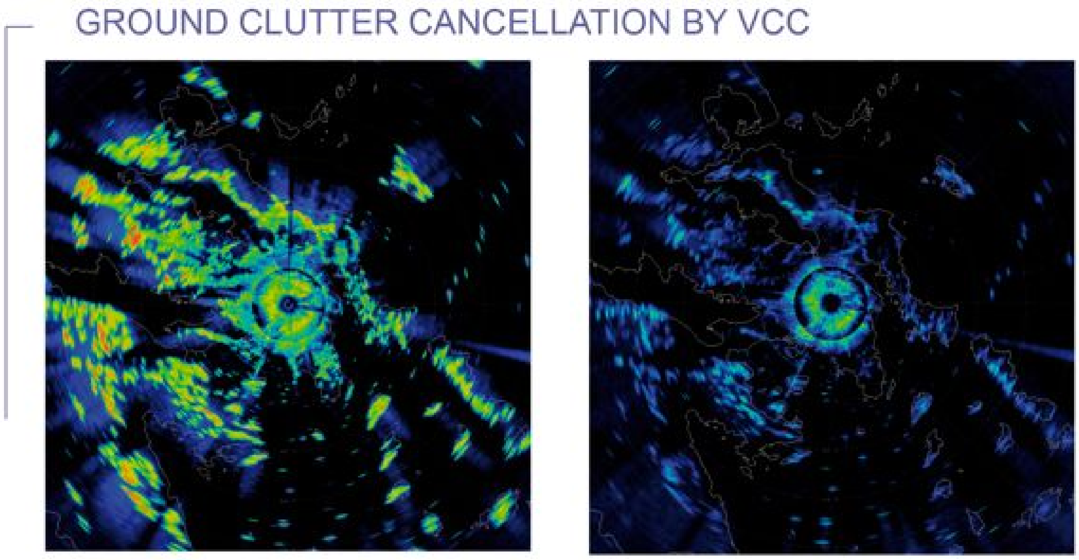

Figure E.2: Ground clutter cancellation by VCC

E.2 Range Azimuth Gating

Range Azimuth Gating is a sophisticated mitigation technique used in radar systems to improve target detection and reduce the impact of unwanted returns, such as clutter and noise. This mitigation technique is employed to isolate specific regions of interest within the radar coverage area. It allows the radar to focus on targets within defined ranges and azimuths while suppressing returns from other areas.

RAG combines two types of discrimination. Spatial discrimination involves limiting the radar's attention to a specific azimuthal sector, effectively narrowing the area of interest. Range discrimination confines the radar's processing to a predefined range window, excluding returns from outside that range.

RAG is implemented through a specialized processing algorithm in the radar's signal processing system. This algorithm filters and sorts radar returns based on both range and azimuth criteria.

A range window is defined to restrict the radar's analysis to a specific range of distances. This is particularly effective in suppressing unwanted echoes from distant objects or ground clutter. The azimuthal sector defines the angular region within which the radar pays attention. By narrowing this sector, the radar can ignore returns from areas outside the region of interest.

While RAG provides benefits in cluttered environments, it may come at the cost of reduced situational awareness in other parts of the radar coverage area. Therefore, careful consideration is given to setting the gating parameters.

Range Azimuth Gating is a powerful mitigation technique that allows radar systems to effectively filter and process returns based on both range and azimuth criteria. This improves target detection in cluttered environments and enhances the radar's overall performance.

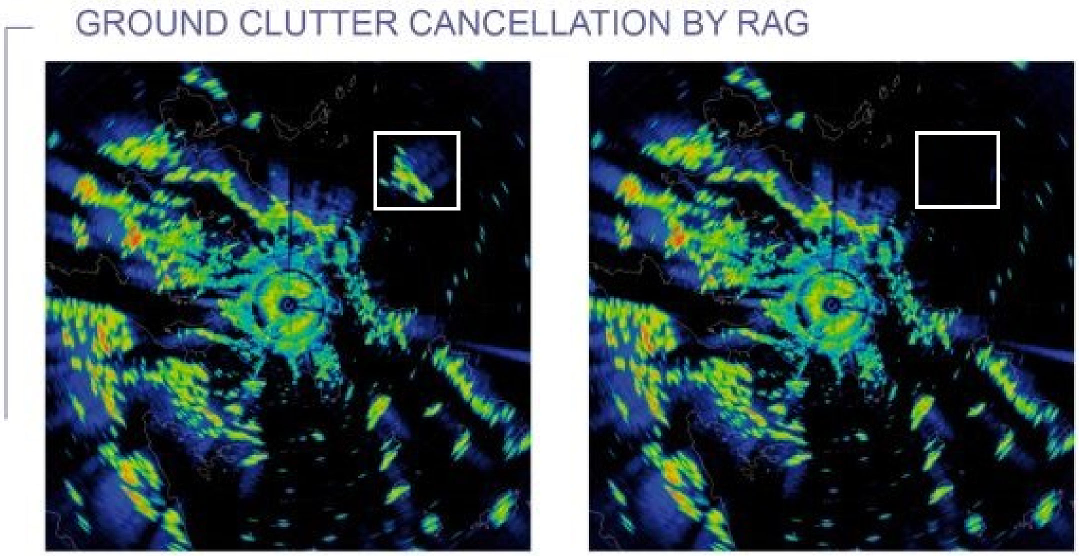

Figure E.3: Ground clutter cancellation by RAG