



## **APPENDIX 5**

**RESPONSE TO AIRNAV IRELAND  
AND SHANNON AIRPORT  
AUTHORITY DAC SUBMISSIONS**

# **Response Statement**

## ***Response to AirNav Ireland and Shannon Airport Authority DAC Submissions & Observations***

### ***An Coimisiún Pleanála Ref No: 320705-24***

with Reference to

*Proposed Development of 9 no. wind turbines, 110 kv substations and ancillary development Knockshanvo Wind energy development within the townlands of Snaty (Massy), Hurdleston, Oatfield, Drumsillagh or Sallybank (Parker), Gortacullin, Aharinaghbeg, Knockshanvo, Cloontra, Clogboolia, Bally- cullen, Cloontra West, Formoyle More, Kilmore, Mountrice, Ballyvorgal South, Crag, Kyleglass, Glenwood, Snaty (Cooper), Ballykelly, Muingboy, DrumsiUagh or Sallybank (Merritt), Kyle, Belvoir, Snaty (Wilson) and Cloontra East, Co.Clare and in the townland of Court, Co. Limerick*

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# Abbreviations

AGL	Above Ground Level
AMSL	Above Mean Sea Level
ANSP	Air Navigation Service Provider
ANI	AirNav Ireland
ARP	Airport Reference Point
ATC	Air Traffic Control
ATCSMAC	Air Traffic Control Surveillance Minimum Altitude Chart
BRA	Building Restricted Area
DME	Distance Measuring Equipment
DoD	Department of Defence
EAS	Emergency Aeromedical Service
GASU	Garda Air Support Unit
GP	Glide Path
HLS	Helicopter Landing Site
IAA	Irish Aviation Authority
ICAO	International Civil Aviation Organization
IFP	Instrument flight Procedure
ILS	Instrument Landing System
MSSR	Monopulse Secondary Surveillance Radar
NAVAIDS	Navigational Aids
NATS	National Air Traffic Services (UK)
NM	Nautical Miles
OLS	Obstacle Limitation Surface
PSR	Primary Surveillance Radar
RWY	Runway
SAA	Shannon Airport Authority
SID	Standard Instrument Departure
STAR	Standard Arrival Route
SSR	Secondary Surveillance Radar
VOR	VHF Omni-directional Range Station

# Appendices

Appendix A	251001 Knockshanvo Meeting Notes with AirNAV_For Issue (005)
Appendix B	AirNav Surveillance Description of Woodcock Hill Radar Signal Deflections
Appendix C	CL-6005-RPT-005 v2.0 Knockshanvo Windfarm Radar Mitigation Options
Appendix D	TNO Capability Statement
Appendix E	PERSEUS overview ( Program for the Evaluation of Radar Systems in an Extended Urban Setting
Appendix F	TNO Presentation ( Reference to existing Wind Farms around Schiphol Amsterdam )
Appendix G	TNO Detailed Engineering Assessment due to Wind Turbines at Knockshanvo
Appendix H	TNO Service Coverage Maps ( Shannon Secondary Radar Combined with Boolynagleragh Wind Farm )
Appendix I	TNO – Detailed Engineering Assessment – Australian Case Study
Appendix J	Eurocontrol – How to Assess the Potential Impact of Wind Surveillance Sensors – Impact Assessment method Extract
Appendix K	TNO – Experience on Wind Turbines Impact on Radars

# References

- [1] Appendix 15-6 – Violet Hill Wind Farm 2020 - 2022 Pre-Planning Consultations
- [2] Appendix 15-6 - 1Violet Hill WF Aviation Review
- [3] Appendix 15-6 - Violet Hill Wind Farm Flight Inspection Check Assessment
- [4] Appendix 15-6 - Violet Hill Wind Farm Radar Surveillance Desktop Review
- [5] Appendix 15-6 - Violet Wind Farm - IAA Consultations
- [6] Appendix 15-6 - IFP Safeguarding Assessment - Violet Hill Wind Farm
- [7] Appendix 15-6 - Violet Hill Wind Farm Impact on ILS Flight Inspection
- [8] Appendix 15-6 - Violet Hill Wind Farm Radar Assessment
- [9] Appendix 15-6 - Concept Design ATCSMAC Shannon Airport
- [10] Appendix 15-6 - Shannon Runway 24 Special ILS Flight Inspection
- [11] Appendix 15-6 - Email Correspondences with Flight Calibration Services Ltd (FCSL)
- [12] Appendix 15-6 - Knockshanvo Wind Farm - Aviation Review Statement
- [13] Appendix 15-6 - Knockashanvo Windfarm - Radar Mitigation Options
- [14] Appendix 15-6 - IFP Safeguarding Knockshanvo Windfarm
- [15] Appendix 15-6 - CAP670
- [16] Appendix 15-6 - State PBN Implementation Plan for Ireland
- [17] SUR.ET1.ST01.1000-STD-01- 01 - EUROCONTROL STANDARD DOCUMENT FOR RADAR SURVEILLANCE IN EN-ROUTE AIRSPACE AND MAJOR TERMINAL AREAS
- [18] AIP IRELAND - ENR 1.6 RADAR SERVICES AND PROCEDURES
- [19] L. Vinagre and K. Woodbridge, "Secondary surveillance radar monopulse target azimuth error estimation due to obstacle shadowing," in IEEE Radar Conference. Radar into the Next Millennium (Cat. No.99CH36249), Waltham, MA, USA, 1999
- [20] L. Vinagre and K. Woodbridge, "Modelling and prediction of obstacle shadowing on secondary surveillance radar target azimuth," *IEE Colloquium on Radar System Modelling (Ref. No. 1998/459)*, London, UK, 1998, pp. 15/1-15/4, doi: 10.1049/ic:19980774. "
- [21] EUROCONTROL Guidelines for Assessing the Potential Impact of Wind Turbines on Surveillance Sensors – GUID-0130 – 9/9/2014

# 1. Introduction

FuturEnergy Knockshanvo Designated Activity Company ( hereafter referred to as “the Applicant”) was invited by An Coimisiun Pleanála on 18 September 2025 to make a submission on the observations received in relation aviation safeguarding concerns against planning application for the proposed Knockshanvo windfarm development.

An online submission, dated 27 September 2024, was issued by The Irish Air Navigation Services trading as AirNav Ireland (hereafter referred to as AirNav) to An Coimisiun Pleanála, RE: Case No. ABP-3\_1\_2215-24 in relation to the proposed Knockshanvo windfarm development.

Another submission, dated 14 October 2024, was issued by Shannon Airport Authority DAC (hereafter referred to as Shannon Airport) to An Coimisiun Pleanála, Re: Case No. ABP-320705-24 (Private Development-Application) in relation to the proposed Knockshanvo windfarm development, where they state that they object to the proposed development proceeding as they share, with the their colleagues in AirNav, the same technical areas of concerns which at a minimum require more analysis.

This Response Statement addresses the observations received in relation to the objections raised against the proposed development on the basis of

- the potential to adversely affect the provision of safe and efficient Air Traffic Services and the Instrument Flight Procedures ( IFP's ) flown by aircraft arriving and departing Shannon Airport
- having potential impacts to the performance the radar surveillance system at Woodcock Hill in the form of radar beam deflections, reflections and shadowing from the wind turbines
- compromising the Woodcock Hill radar’s compliance with EU performance criteria required for 5NM horizontal separation of aircraft transiting En-route Irish Airspace and also the 3NM horizontal separation of aircraft in Dublin airspace
- AirNav’s continued objections since 2018, having previously engaged with multiple developers to similar proposed developments in this area

## 1.1 Response Statement Overview

- 1.1.1 This Response Statement document has been prepared on behalf of the Applicant by Ai Bridges, who took on the role of Project Co-Ordinator. The document was reviewed by the Project Management Team acting for the Applicant.

### **AirNav and Shannon Airport Submissions :**

- 1.1.2 This Statement presents the Applicants response to the observations that were submitted by AirNav and Shannon Airport in October 2024, by way of the reference to the Appendices that were attached with the detailed technical aviation assessments previously submitted as part of the SID application in 2024 (hereafter referred to as “the Application”). These appendices are included in the References of this Response Statement

### **Consultations - Industry Engagements :**

- 1.1.3 The consultations and engagements with AirNav in 2020 to 2022 are shown in Appendix 15-6 – Violet Hill Wind Farm 2020 – 2022 Pre-Planning Consultations.

- 1.1.4 The Applicant undertook additional consultations with AirNav and arranged a meeting in October 2025 to better understand the major concerns in relation to the proposed development.
- 1.1.5 Following this further engagement the Applicant prepared meeting minutes, as per their understanding ( as shown in Appendix A ), as per the extract
- *re-design of the IFP's has been put back to 2027 in Q2/Q3, however that the implementation of the PBN plan will reduce the impact to IFP's and the potential for the proposed development at act as obstacles have been provisioned for*
  - *that they are carrying out a cumulative impact assessment on the potential wind farm in East Clare, and the minimum altitude sector required to manage flights descending into Shannon, which can be achieved at the higher altitude of 2400ft.*
  - *that AirNav's the remaining issue in relation to radar was deflections and false signals caused by wind turbines, which can degrade radar accuracy and safety in controlled airspace, especially beyond 150-250 NM from radar sites*
  - *AirNav highlighted lack of evidence supporting co-existence of large wind farms and radar operations without adverse effects and that Aviation authorities are not permitted to degrade radar safety standards, and any mitigation must be proven not to compromise operational safety.*
  - *Further meetings once detailed analysis is carried out and to be provided to AirNav so as to continue collaboration between AirNav and the Applicant, aiming to resolve outstanding safety issues and provide clear evidence to support the project.*
  - *AirNav expressed openness to reviewing evidence from developers or consultants demonstrating radar coexistence with wind turbines, that would show no impacts at distances of 150NM – 250NM and that ideal evidence would include radar data screenshots showing no adverse deflections within safeguarding zones.*
- the context on the significance of Woodcock hill Radar and how it serves en-route phases of flights and manages significant traffic from the east. AirNav stated that any interference or false radar signals generated by wind turbines could impact operations during the operation of these flight phases.
  - concerns in relation to radar deflections and false signals caused by wind turbines, which can degrade radar accuracy and safety in controlled airspace, especially at distances between 150NM and the maximum range 256NM, from the radar
  - the lack of evidence supporting co-existence of large wind farms and radar operations without adverse effects. Aviation authorities are not permitted to degrade radar safety standards, and any mitigation must be proven not to compromise operational safety and that this reflects the only remaining issue.
  - That potential mitigation may include upgrading radar systems or installing additional radar sites to maintain coverage and safety. There are, however, the complexity, cost, and technical challenges of such upgrades, for radar equipment and infrastructure, with ongoing maintenance expenses. Alternative technologies like wide-area multilateration were considered but found suboptimal for the region's unique geography
  - That there is an openness to reviewing evidence from developers or consultants demonstrating radar coexistence with wind turbines, at distances of 150NM to 250NM and that deal evidence would include radar data screenshots showing no adverse deflections within safeguarding zones.
- 1.1.6 There were a number of engagements at industry level, in July 2025, which was initiated by Wind Energy Ireland ( hereafter referred to as "WEI") with representation from the Department of Transport and AirNav. A report (hereafter referred to "Deflections Report") was prepared by

AirNav ( as shown in Appendix B ) on the matter of Surveillance Description of Woodcock Hill Radar Signal Deflections. The Applicant , as a WEI member, became aware of this report. This report specifically addresses the major concern of radar beam deflections , impacting the measured positions of aircraft at distances beyond out to 400km, caused by a telecoms mast located 730m from the Woodcock Hill Radar.

- 1.1.7 In their Deflections Report AirNav identified this example of deflections which has occurred and indicated their concern that similar deflections would occur due to the proposed windfarm developments in East Clare Wind Farm wind turbine generators. AirNav provided screenshots of the radar analysis picture using Eurocontrol analysis software of the radar data recordings taken on dates in March 2025 and June 2025.
- 1.1.8 AirNav conclude in their Deflections Report by stating that they require evidence or case study examples that wind turbines deployed within comparable ranges ( as the developments in East Clare and currently in planning ) and in view of an En-route secondary radar have not impacted the surveillance performance of that radar. AirNav require this evidence in line with test and validation evidence for AirNav and IAA regulatory approvals. AirNav state in their Deflections Report that they have communicated this requirement for in-service evidence in all meetings with the Wind farm developers. AirNav state in their Deflections Report that radar deflections, reflections and shadowing by wind turbines within the safeguarding zones all remain a concern.
- 1.1.9 Following the consultations and industry engagements between WEI , Department of Transport and AirNav, the Applicant initiated the Impact Assessment Process as set out in Eurocontrol Guidelines ( as shown in Appendix J ) and which calls out the wind energy developer responsibilities as well as the ANSP's responsibilities. The applicant acted in the spirit of these Guidelines and engaged with their aviation experts Cyrrus and TNO to conduct Detailed Engineering Assessments to address the further requests examples and case studies.

#### **Instrument Flight Procedures - Radar Assessments :**

- 1.1.10 The Applicant commissioned Ai Bridges to engage aviation experts and consultants to perform the required in-depth analysis and to provide supporting case study evidence which would provide AirNav with a high level of confidence that there is a practical way to proceed with a safety assurance case for potential mitigation options to be submitted for review and approval by the AirNav Safety Management Unit to take before the IAA, as regulator.
- 1.1.11 Ai Bridges commissioned Cyrrus Limited in November 2025 to conduct a review of the IFP Safeguarding Assessment<sup>[14]</sup> and Radar Mitigations Options Assessment<sup>[13]</sup> that they previously prepared in 2023 to 2024 with a view to revising and updating same to address the key observations raised by AirNav in relation to the Instrument Flight Procedures (IFP) at Shannon Airport and to the Woodcock Hill Secondary Surveillance Radar.
- 1.1.12 Cyrrus completed their review and no updates were applied to the IFP Safeguarding Assessment as previously completed based in the current Instrument Flight Procedures in use at Shannon Airport.
- 1.1.13 Cyrrus also completed a review of the Radar Mitigations Options Assessment Report<sup>[13]</sup> that was completed in 2024 as part of the planning application. Cyrrus updated by inclusion of additional sections 9 and 10 addressing Operational Considerations and Surveillance Coverage Assessments respectively in the context of the concerns raised by AirNav and Shannon Airport. This update references Operational Requirements for Radar Surveillance in En-Route Airspace and Major Terminal Areas with specific references contained under the following areas :

- Surveillance Requirements for Shannon Airport ( to ensure the minimum safe altitudes )
  - En-Route Services
  - IFP Safeguarding and Mitigation
  - Vertical Surveillance Coverage
  - Horizontal Surveillance Coverage
  - Cumulative Assessment
- 1.1.14 As requested by its aviation experts, Cyrrus, the Applicant requested the ARTAS data from AirNav Ireland to provide the actual radar recordings from the Woodcock Hill MSSR so that this data could be analyzed and assess the reports for deflections caused at distances of 150km – 400km out from the Woodcock Hill MSSR.
- 1.1.15 This data was requested to allow aviation experts acting on behalf of the Applicant to accurately model and simulate the deflections from the telecoms mast and how closely this simulation would correlate to the real-world aircraft track position errors that are being seen by Air Traffic Controllers on their radar screens. This is a key issue and can only be resolved through modelling the actual Radar data related to observed deflections. AirNav indicated they were unable to provide the data due to confidentiality issues.

**Evidential Support – Case Studies :**

- 1.1.16 Ai Bridges also engaged with a Dutch Consultant, TNO, in November 2025 to conduct a series of assessments. As stated in their Capability Statement ( as shown in Appendix D ) TNO have a track record for over 30 years in assisting wind farm developers and supporting Air Navigation Service Providers in a number of countries. They accurately model and simulate the probability of detection and coverage for both primary and secondary radars for operational civil and military radar systems.
- 1.1.17 TNO use their own proprietary software tool, PERSEUS ( as shown in Appendix E- Program for the Evaluation of Radar Systems in an Extended Urban Setting ) to accurately model to predict the actual levels of potential impact areas caused by the proposed development. Compliance with existing guidelines including ICAO EUR DOC 015, CAP 764 and Eurocontrol Guidelines (2014).
- 1.1.18 Ai Bridges commissioned TNO to perform the Detailed Engineering Assessment (DEA) ( as shown in Appendix G ) against the proposed development in line with the Eurocontrol Guidelines to assess the potential impact on the MSSR at Woodcock Hill. As part of this DEA a cumulative impact assessment of the Oatfield development was included. The Oatfield development is also in the planning process and is in close proximity to the proposed Knockshanvo development. As part of the existing baseline TNO also considered the consented wind farm developments at Carrownagowan, Fahybeg and Lackareagh as all wind farms are inside the 16km distance assessment zone according to Eurocontrol Guidelines.
- 1.1.19 The Applicant has provided this DEA Report to AirNav for this review in January 2026. At the time of writing this Response Statement, a response has not been received from AirNav in relation to this DEA Report.
- 1.1.20 Ai Bridges has also requested TNO to provide case study reports to support that the assessment methodology they applied, has been validated against real-world MSSR track recordings of aircraft. TNO provided a case study example (details of which are contained in Appendix F - slides 12 to 19 ) of how they modelled the impacts of planned wind farm 8km north of the MSSR radars at Schiphol Airport. The TNO methodology has been validated by modelling of the impacts of an Air Traffic Control tower, at a distance of 1.9km, on the MSSR Radar (Thales RSM970S) at Brussels Airport. The case study shows that TNO can accurately demonstrate a close match between the real-world recorded MSSR

track of an aircraft as a distance of 90NM from the MSSR and their simulated model. TNO describes in this case study how their modelling and simulations informed the Dutch ANSP in their selection of an optimum mitigation measure solution.

- 1.1.21 TNO also highlight, in their conclusions of this case study, references to other forms of mitigation which are available but that this is the responsibility of the ANSP in question to decide what the most suitable form of mitigation is, and which option is operationally acceptable.
- 1.1.22 TNO were also requested to provide examples and evidence of mitigation measures. TNO have provided some examples for their experience in the Netherlands ( as shown in Appendix K - pages 17 to 27 ) where some mitigation measure solutions have been highlighted including radar system adaptations such as radar fusion of data from multiple radars, combining with other radars, realisation of additional radars including in-fill radars, 3D radars in place of 2D radars and processing improvements within the radars. TNO have briefly expanded on some of these mitigation concepts which also mirror the position taken by Cyrrus in their suggested approach to mitigation measure solutions.
- 1.1.23 The applicant also requested Ai Bridges to commission a Detailed Engineering Assessment (as shown in Appendix H) of an operational wind farm in the Republic of Ireland which is located inside the 16km assessment zone of an operational MSSR radar. The Boolnagleragh Wind Farm in Co. Clare was selected as some of the operational wind turbines are located inside a distance of 16km from the Shannon Airport MSSR. As the performance of radar systems can be negatively influenced by wind turbines in their vicinity, EUROCONTROL has issued guidelines, on how to assess the potential impact of wind turbines in line of sight of MSSR of Shannon Airport. TNO were also commissioned to prepare the Service Coverage map of the En-Route MSSR at Shannon and identify the areas where the angle measurement of the MSSR may be influenced by the wind turbines of the existing Boolynaglegagh wind farm. TNO were able to determine the service coverage maps of the MSSR at Shannon, as modelled without and with the wind turbines at Boolynaglegagh windfarm.
- 1.1.24 TNO also provided an additional case study (as shown in Appendix I) of an Australian Wind Farm developer to conduct a detailed engineering assessment of the potential effects of a 70-turbine wind farm development on the MSSR performance of radars operated by the Australian ANSP, Airservices Australia (ASA). The TNO modelling tool accurately identified the issues of interference and assisted the ANSP to model the worst-case scenario effects of the potential impacts of proposed the wind farm on MSSR Radar. TNO used their software simulation tool to predict the Off Boresight Errors caused by the 70-turbine wind farm on the MSSR performance
- 1.1.25 TNO evidenced the accuracy of the model by showing the correlation between the software predicted position error plot against the real-world track error. This was achievable based on the data that was provided to TNO from the radar manufacturer. The simulation provided the ANSP with sufficient assurance that a neighbouring MSSR radar at Mount Macedon would provide the required radar coverage picture to air traffic controllers. The wind farm development was consented and a mitigation measure solution was informed based on the modelling of the wind farm impacts
- 1.1.26 The Applicant has noted that it has provided the evidence that has been called for by AirNav that shows that demonstrates radar beam deflections caused by wind farms can be accurately modelled and that these impacts can be mitigated out by an optimum mitigation measure solution.
- 1.1.27 The Applicant believes that the additional detailed engineering assessments of the proposed development, the consented windfarms (Carrownagpowan, Lackerragh Fahy-beg) and the Outfield project meets the AirNav testing and validation requirements. The Applicant believes

that they have provided valid precedence of the co-existence of wind farms and operational surveillance radars in close proximity.

- 1.1.28 The Applicant also believes the detailed engineering assessment, conducted by TNO, against the operational Boolynagleragh wind farm provides a valid precedent of where a windfarm is operating inside the recommended Eurocontrol impact assessment zone of 16km remain operationally acceptable. This outcome of this assessment demonstrates that the operational wind turbines are within line of sight of the Shannon MSSR radar and are shown under the results of the further assessment that the turbines have the potential to impact performance of the Shannon MSSR, however this wind farm is operationally tolerable for AirNav.

### **Navigational Aids and Communications Systems**

- 1.1.29 The Applicant notes that there was no specific objection or concern raised by either AirNav on Shannon Airport in their submission in October 2024 in relation to any adverse effects of the proposed development may have on the Flight Inspection Procedures and profiles associated with the Shannon Airport Runway 24 Instrument Landing Systems. In August 2021, the Applicant previously commissioned FCSL, an IAA approved service provider, to conduct an assessment against the 18-turbine layout. The findings were that ILS flight inspection procedures would potentially be impacted and the procedures would have to be flown at an increased height which could result in an increased flight inspection costs. FCSL recommended that flight trials be conducted to ensure correct ILS received operation at increased ranges. Following additional flight trials, FCSL confirmed that adequate signals were received when the flights were conducted at 2,600ft and 3,000ft. FCSL confirmed that when the flight inspection operations are conducted in instrumented metrological conditions at 2,7600ft and the 18-turbine layout would not have any effect on the Shannon Airport Runway 24 flight inspection procedures.

### **Shannon Airport Authority – Further Comments & Conditions to Planning**

- 1.1.30 The Applicant has addressed the comments as set out by Shannon Airport in relation to the communications, navigation and surveillance systems used by AirNav for the separation and safety of aircraft. The Applicant has also noted the comments in relation to the establishment of OLS to maintain aerodrome free from obstacles.
- 1.1.31 The Applicant notes that an Annex 14 Obstacle Limitation Surfaces Assessment<sup>12)</sup> was carried out and as shown in Section 2.1 that all of the 9-turbines are outside the OLS surfaces and will not have an adverse impact on the aerodrome.
- 1.1.32 The Applicant also notes the Shannon Airport position that it does not concur that there will be no residual impacts as concluded in the Aviation Assessment Summary (Chapter 15-6 - Knockshanvo Wind Farm Aviation Assessment Summary report)
- 1.1.33 The Applicant notes that the outcomes of the detailed IFP and the Radar Safeguarding Assessments carried out by Cyrrus provide mitigation measure options that have been presented for consideration by AirNav and should an optimum mitigation measure be agreed and implemented through further collaboration, the Applicant notes that outcome of the residual impacts would reduce to a No Impact condition.
- 1.1.34 The Applicant has addressed the notice to conditions as part of general guidance for windfarm developments as set out by Shannon Airport in its submission.
- 1.1.35 The Applicant has addressed the requirement for consented wind turbines within 45km of Shannon Airport and greater than 100m in height be included in the IAA Electronic Air

Navigation Obstacle Dataset and notes that in the event of a planning consent that it will comply with the condition.

- 1.1.36 The Applicant also notes its intention to comply with any condition in relation to aviation lighting as per Chapter Q (Visual Aids for Detecting Obstacles) of the Certification Specifications for Aerodrome Design - Issue 6 to EASA standard for extensive objects to be applied against consented windfarm developments.
- 1.1.37 The Applicant also notes its intention to comply with any conditions in relation to any crane activity by completing the Shannon Airport Crane Operations application form at least 30 days in advance of any crane erection taking place, in support the appropriate level of assessments to be carried out by the Shannon Airport and Air Nav against possible interferences by cranes with communication, navigation and surveillance systems.

## 2. AirNav Ireland and Shannon Airport Authority Observations :

The applicant, Future Energy Knockshanvo DAC notes the submissions and observations below which set out the objections, concerns and comments as received from AirNav Ireland and from Shannon Airport Authority DAC respectively.

In assessing the submissions relevant aviation stakeholders, the roles of each stakeholder was considered and set out below. While there was no submission from the Irish Aviation Authority ( hereafter referred to as "IAA") the role of the IAA , as Aviation Regulator is also included.

**Irish Aviation Authority** : is responsible for regulating the air navigation sector, including safety and economic regulation. It also regulates other aspects of Irish aviation, such as airport safety and security.

**AirNav Ireland** : provides air traffic control, aeronautical information, North Atlantic communications, and related services. It operates as a separate entity from the IAA, responsible for the day-to-day operation of air navigation services provision.

**Shannon Airport Authority DAC (SAA)** is responsible for the management, operations and development of Shannon Airport and also takes responsibility all aspects of aviation safeguarding of the aerodrome facility of Shannon Airport

The IAA, AirNav and Shannon Airport are all distinct entities. AirNav Ireland provides air navigation services provision, SAA provides management, operations and development at Shannon Airport while the IAA focuses on national aviation safety and economic regulation. The IAA's air navigation service provision function was separated and established as a standalone commercial semi-State body, AirNav Ireland, on April 30, 2023. Both AirNav and Shannon Airport bodies are regulated by the IAA.

It is the role of AirNav, as Air Navigation Service Provider if they identify a safety issue, where mitigations for a proposed wind farm development are identified that are within appropriate risk tolerance levels, a safety case would have to be presented to the IAA, as regulator. The regulation, specifically EU Regulation 2017/373 in the context of Irish Airspace, sets out common rules for air traffic management and air navigation by service providers, their risk-based oversight by the IAA, it provides a framework for the IAA to manage non-compliance through analysis and enforcement measures and establishes a structured system for the IAA to analyze non-compliance findings, decide on enforcement measures based on safety risk, and ensure corrective actions are taken.

### 2.1 AirNav Ireland Observations :

2.1.1 AirNav Ireland states that it maintains its objections to the proposed development as follows :

**Objection # 1** :*AirNav Ireland provides Air Traffic Services (ATS), including Instrument Flight Procedures (IFPs) flown by aircraft arriving at and departing from Shannon Airport. The proposed development would introduce new obstacles in the vicinity of Shannon Airport which have the potential to compromise several of these IFPs, adversely affecting the provision of safe and efficient ATS at that airport.*

**Objection #2** :*AirNav Ireland is responsible for the Communications, Surveillance and Navigation systems which are essential to the safety critical air traffic services we provide*

at Shannon Airport and in Irish controlled airspace. These services include the provision of ATS to approximately 370,000 aircraft each year which overfly Ireland while operating between Europe and North America and to almost 310,000 flights to/from the Irish State Airports. The proposed windfarm development would have a significant negative impact on the performance of the radar surveillance systems at our Woodcock Hill facility. The proximity and scale of the proposed development would lead to radar beam deflections, reflections, and shadowing from the wind turbines and there are no credible and implementable mitigations that could be applied to the Woodcock Hill radar to eliminate these effects. This development would compromise the Woodcock Hill radar's compliance with EU mandated surveillance performance criteria required to support 5 Nautical Mile horizontal separation of aircraft in En-Route Irish airspace and 3 Nautical Mile horizontal separation of aircraft in Dublin airspace.

**Objection # 3 :** Since 2018, AirNav Ireland, along with the Shannon Airport Authority (SAA), has engaged with multiple developers for this site (formerly known as the Violet Hill Project) and others in this area, outlining our concerns. On each occasion, we have objected to the proposed development for the aforementioned reasons. AirNav Ireland will continue to object to this development due to the negative impact it would have on the Woodcock Hill radar and the consequential implications for the provision of safe and efficient Air Traffic Services in Irish controlled airspace

**Concern #1 :** MKO, the company representing this development, has previously had interactions with both AirNav and SAA for other developments. It is a matter of some concern that in this instance it appears to be attempting to circumvent the objections of both organisations by engaging directly with ABP.

## 2.2 Shannon Airport Authority DAC Observations :

2.2.1 Shannon Airport Authority DAC made the following comments, as a prescribed body, in respect of this proposed development as follows :

**Comment # 1 :** In this instance, Shannon Airport Authority were not provided by the applicant with notice of this submission as is required under Article 28 (1)(i) of the Planning and development Regulations 2001 (S.I. No. 600/2001) "Notice to Certain Bodies." Previous engagements with MKO, the company representing this development on behalf of the applicant, FuturEnergy were undertaken regarding this site and as such a level of expectation would have been that consultations would have continued with both Air Nav Ireland and Shannon Airport as affected aviation stakeholders once the project was deemed as strategic.

**Comment #2 :** In general terms, the siting of wind turbines at this location may have implications for the operations of the communication, navigation and surveillance systems used by Air Nav Ireland for the separation and safety of aircraft. The geographical siting of these turbines may also have implications for the flight paths of aircraft.

**Comment # 3 :** Shannon Airport Authority DAC has specific responsibility to define the airspace around its aerodrome which must be maintained free from obstacles to permit

*the intended aircraft operations at the aerodrome to be conducted safely and to prevent the aerodrome from becoming unusable by the growth of obstacles around it. This is achieved by establishing a series of obstacle limitation surfaces (OLS) that define the limits to which objects (temporary or permanent) may project into the airspace. These surfaces may extend many kilometres outwards from the active runway strip at the aerodrome.*

**Comment # 4 :***With specific reference to the Knockshanvo Wind Farm Aviation Assessment Summary report (Appendix 15-6) produced by Ai Bridges, we note the conclusions outlined therein but do not concur that there are no residual impacts arising from the proposed development of 9 no. turbines at this site.*

- 2.2.2 Shannon Airport notes that it shares the major concerns of our colleagues in Air Nav Ireland who made an online submission on 27/09/2024 in which they have raised several technical areas of concern that at a minimum require more analysis, specifically:

**Concern # 1 :***That this development would introduce new obstacles in the vicinity of Shannon Airport which have the potential to compromise several of the Shannon Airport specific Instrument Flight Procedures (IFP's) thereby adversely affecting the provision of safe and efficient air traffic services at the airport.*

**Concern # 2 :***That the proposed windfarm development would have a significant negative impact on the performance of the radar surveillance systems at the Woodcock Hill radar facility. The proximity and scale of the proposed development would lead to radar beam deflections, reflections, and shadowing from the wind turbines and there are no credible and implementable mitigations that could be applied to the Woodcock Hill radar to eliminate these effects*

**Concern # 3 :***Since 2018, Air Nav Ireland, along with Shannon Airport Authority has engaged with multiple developers for this site (formerly known as Violet Hill wind farm development) and others in this area, outlining our reasonable concerns. On each occasion the proposed development has been objected to due to the negative impact it would have on the Wood- cock Hill radar installation and the consequential implications for the provision of safe and efficient Air Traffic Services in Irish controlled airspace.*

- 2.2.3 Shannon Airport Authority notes that they remains fully supportive of this position and the serious concerns of Air Nav Ireland as outlined and also objects to this development proceeding.

- 2.2.4 Shannon Airport Authority DAC, as part of the general guidance for windfarm developments in the State, also stated that the following conditions/requirements must be imposed in relation to the proposed development :

**Condition # 1 :***If the turbines are within 45km of Shannon Airport's Aerodrome Reference Point (ARP) and are greater than 100m in height they will be required to be included in the IAA Electronic Air Navigation Obstacle Dataset.*

**Condition # 2 :***Also, the developer shall apply the following standard: Chapter Q (Visual Aids for De- noting Obstacles) of the Certification Specifications for Aerodrome Design - Issue 6 contained in the EASA aerodrome rules to the wind turbine development should it receive planning permission as it would be regarded as an extensive object*

**Condition # 3 :***Finally, during the construction phase of the wind farm development if approved, any crane activity on the site must be pre-approved by the completion of the Shannon Airport Crane Operations application form at least 30 days in advance of any crane erection taking place. That is for the appropriate level of assessments to be carried out by the airport and Air Nav Ireland against possible interferences by cranes with communication, navigation and surveillance systems.*

### 3. Applicant Response

The applicant notes the objections raised by AirNav Ireland ( hereafter referred to as “AirNav”) and Shannon Airport Authority DAC ( hereafter referred to as “Shannon Airport”). Each of the objections in Section 2 of this Response Statement and raised in relation to the proposed development are addressed below, by way of the reference to the Appendices that were attached with the detailed technical aviation assessments previously submitted as part of the Application. These appendices are included in the References of this Response Statement.

The additional consultations with AirNav in October 2024 (as shown in Appendix A), where further evidence and case studies were called for, also inform the Applicant’s response.

Each of the objections in relation to impacts of the proposed development o are addressed in the sub-sections 3.1 to 3.4 below

- Instrument Flight Procedures
- En-Route Radar Surveillance sensor at Woodcock Hill facility
- Previous Developments since 2018
- Navigational Aids.

All objections and comments raised by Shannon Airport in its submission have been addressed in the response below under the following headings :

- In general terms may have implications for the operations of the communication, navigation and surveillance systems used by Air Nav Ireland for the separation and safety of aircraft.
- Maintaining aerodrome free from obstacles by establishing obstacle limitation surfaces (OLS)
- Shannon Airport does not concur with conclusion that there are no residual impacts as stated in the Knockshanvo Wind Farm Aviation Assessment Summary report (Appendix 15-6)

The Applicant also notes the notice to conditions as part of general guidance for windfarm developments as set out by Shannon Airport in its submission and these are also addressed in the response below.

The Applicant sets out its response below in relation to each of the objections, comments and notice to conditions as submitted by AirNav and Shannon Airport in relation to the proposed development.

#### 3.1 Instrument Flight Procedures :

In relation to the Air Traffic Services and Instrument Flight Procedures flown by aircraft arriving in and out of Shannon Airport, AirNav objects to the proposed windfarm development as stated below

*AirNav Ireland provides Air Traffic Services (ATS), including Instrument Flight Procedures (IFPs) flown by aircraft arriving at and departing from Shannon Airport. The proposed development would introduce new obstacles in the vicinity of Shannon Airport which have the potential to compromise several of these IFPs, adversely affecting the provision of safe and efficient ATS at that airport.*

In relation to Instrument Flight Procedures, Shannon Airport Authority DAC notes that it shares the concerns of Air Nav Ireland that at a minimum require more analysis and state that

*That this development would introduce new obstacles in the vicinity of Shannon Airport which have the potential to compromise several of the Shannon Airport specific Instrument Flight*

*Procedures (IFP's) thereby adversely affecting the provision of safe and efficient air traffic services at the airport.*

### **3.1.1 Consultations**

For completeness and a full perspective of the consultations and engagements in their entirety, the Violet Hill Wind Farm 2020 - 2022 Pre-Planning consultations<sup>[1]</sup> are included, noting that during the feasibility stage for the proposed development in 2020 the preliminary design for the proposed development was for an 18-turbine site - at this time the project was known as Violet Hill. This document summaries all previous engagement with AirNav and Shannon Airport. with all the Aviation Stakeholders ( AirNav Ireland and Shannon Airport Authority ) in order to provide the background to consultations in relation to the proposed Knockshanvo 9-turbine development.

In November 2021 an initial consultation was sent to AirNav in relation to the 18-turbine layout at Violet Hill ( formerly known at that time as "IAA", and hereafter referred to as AirNav ) for their review. In November 21 the AirNav, specifically in relation to IFP's, noted the following in their consultation response ( as referenced in Appendix 1.1 – IAA Consultations )

- *Instrument flight procedures (IFP's): Surveillance minima as well as Instrument flight procedures could have some impact dependent on the wind turbine elevations*

On 04 February 2022, a consultation response was received from AirNav where they acknowledged the proactive engagement by Ai Bridges and the involvement of Cyrrus in relation to the various assessments received. In relation to IFP's AirNav then went on to state the following in relation to the Radar Assessment following review :

In their concerns regarding Instrument Flight Procedures the AirNav highlight their concerns while also referencing the State PBN Implementation Plan as to possible ways to address the impacts on the conventional VOR Runway 24 IAP. AirNav also refers to the Required Navigational Performance (RNP) approaches in combination with the ILS-based final approaches as part of the State PBN plan. AirNav allow for the possible withdrawal of the conventional VOR approach on the basis of the State PBN plan :

- *"Increasing of PDG from 3.5% to 4.0% for affected SIDs: Agreed in principle and can be incorporated in updated IFP designs planned for late 2022. This is also consistent with non-SID departure instructions increased PDG"*
- *"VOR RWY 24 IAP: Impact noted and mitigations understood. These are not however consistent with our requirements for SDF etc. If the development goes ahead, I would recommend withdrawal of the VOR IAP on the basis that this would be in line with the State PBN plan and that RNP IAPs are planned for Shannon during 2022"*

AirNav also raised operational aspects in the application of Surveillance Minimum Altitude Chart minima with two major ATC concerns:

- *"Vectoring of traffic for short finals, amended SMAC minima has the potential to increase ATCO workload in vectoring traffic with less flexible minima on shorter finals for RWY 24"*
- *"For aircraft operations the potential false capture of the GP with more constrained altitudes is of concern particularly as RWY 24 is the CAT II ILS approach for Shannon Airport"*
- *"Lastly, there is a likelihood that the 3° Glide Slope might need to be increased to cater for these new obstacles, which is not acceptable operationally"*

On 23 January 2023 the Environmental Consultants MKO sent a consultation, on behalf of the Applicant, to Shannon Airport, in relation to the final proposed 9 turbine Knockshanvo Wind Farm development.

*“ Please find attached a scoping document for FuturEnergy Irelands (FEI) proposed construction of a wind energy development at Knockshanvo, approximately 3km south of Broadford, Co. Clare. The proposed site covers an area of approximately 931 hectares. At this scale the site has the potential to accommodate a wind energy development in excess of 50 Megawatts. The number and layout of turbines will be defined during the upcoming project design stages.*

*The following application will be seeking determination from An Bord Pleanala in relation to the developments Strategic Infrastructure Development Status. If the Proposed Development does not fall under Section 182A of the Planning and Development Act 2000, an application for planning permission for any relevant works will be made to Clare County Council.*

*As part of the scoping exercise for the proposed development, we would welcome any comments in relation to the proposed project.”.*

On 03 February 2023 AirNav sent a response to the Environmental Consultants. The specific response in relation to the proposed development calls out for further analysis.

*“Correspondence below and attached refer, with thanks to Paul Hennessy for passing on this.*

*From an IAA Air Navigation Service Provider (ANSP) perspective, there are areas where we would need more analysis:*

- ***Instrument Flight Procedures (IFPs) Shannon Airport:***
  - *The Grids displayed represent the Max Above Mean Sea Level elevation of any new obstacles, above which, an IFP Assessment is needed.*
  - *In the area around Knockshanvo as per the attached report, there are a range of grid values from 361m to 401m. I understand that the proposed blade-tip heights are c.170m. This equates to a c.370m AMSL elevation based on a general site elevation of 200m. Added to this any potential craneage used during construction will need a full IFP Assessments.*

On 01 October 2025 an online meeting took place with AirNav and IFP's were discussed. The applicant provided a summary of the specific points discussed in relation to IFP's as part of the applicant's own meeting minutes (as shown in Appendix A) A copy of these minutes were sent to AirNav on 28 October 2025. The summary points in relation to the IFP's are shown below. At the time of writing, a response from AirNav is still awaited. The relevant extract from the meeting minutes prepared by the Applicant is shown below

- *Redesign of the IFP's scheduled for release in September 2025 has been put back to Q2/Q3 2027,*
- *The implementation of the PBN plan will reduce the impact to flight procedures and the potential as the obstacles have been programmed.*
- *AirNav are in the process of carrying out a cumulative impact assessment with FCSL on the potential wind farm in East Clare, and the minimum altitude sector required to manage flights descending into Shannon. This can be achieved at the higher altitude of 2400ft.*

### 3.1.2 Technical Assessments

The applicant notes the AirNav concern that the proposed development would introduce new obstacles in the vicinity of Shannon Airport and which have the potential to compromise several of these IFPs, adversely affecting the provision of safe and efficient ATS at that airport

The initial consultations with AirNav, between November 2021 to April 2022 and in 2023 with the EIA Consultants are detailed in Section 3.1.1. Following these engagements a number of wind farm design changes occurred which ultimately resulted in the site reducing in scale from 18 turbines to the final proposed 9 turbine layout for which permission is being sought. Several turbines were removed from the original layout to mitigate impacts on identified constraints which was in part informed by impacts on aviation infrastructure. This 9-turbine layout forms the basis of the proposed Knockshanvo development submitted in the Application.

The applicant notes that it previously commissioned a detailed technical assessment of the Instrument Flight Procedures for Shannon Airport. In October 2023 Ai Bridges engaged Cyrrus Limited to conduct an initial detailed technical Instrument Flight Procedure Safeguarding Assessment. The findings presented by Cyrrus in their IFP Safeguarding Assessment (shown in Appendix 12 - IFP Safeguarding Knockshanvo Windfarm Aviation) in March 2024 concludes that the proposed development would, without mitigation, have an impact to the following Instrument procedures for Shannon Airport:

- Standard Instrument Departure (SID) RWY06 Procedures
- VOR Instrument Approach RWY24
- Air Traffic Control (ATC) Surveillance Minimum Altitude Chart

In the concluding statement of their IFP Safeguarding Assessment ( as referenced in Appendix 12,Section 3 - IFP Safeguarding Knockshanvo Windfarm ) Cyrrus state that while the proposed windfarm does impact the currently published IFPs for Shannon Airport, the mitigation options provided are for Shannon Airport Authority to consider which will be subject to their Safety Management System (SMS) requirements and the commercial benefit of accepting the mitigation.

### 3.1.3 Mitigations Options

Cyrrus present mitigation options in their IFP Safeguarding Assessment (as shown in Appendix 12, section 3 ) to mitigate the impacts to the Instrument Flight Procedures at Shannon Airport. Cyrrus also present additional design options in section A.2 which offer viable mitigation measures to remove the impacts on the flight procedures and ATCSMAC Charts.

The mitigation options presented by Cyrrus draw reference to an increase in Procedure Design Gradient Required Navigation Performance (RNP). Taking these in turn :

- Standard Instrument Departure (SID) RWY06 Procedures  
During the engagements with the IAA in 2022 they state that Instrument Flight Procedure designs were planned for Shannon Airport in 2022 and that this would enable the mitigation of the impact in relation to the Standard Instrument Departure (SID) i.e. the IAA agreed in principle that increasing the Procedure Design Gradient for the SID departure would be incorporated in updated IFP designs by late 2022 as shown in their consultation response below:

*“ Increasing of PDG from 3.5% to 4.0% for affected SIDs: Agreed in principle and can be incorporated in updated IFP designs planned for late 2022. This is also consistent with non-SID departure instructions increased PDG ”*

- VOR Instrument Approach RWY24

The IFP Safeguarding Assessment completed by Cyrrus in December 2023 in Appendix 12 highlights that the Instrument Flight Procedures for approach onto Runway 24 and Instrument Departure from Runway 06 for Shannon Airport will be impacted. The IAA have stated (Appendix 1.4 – “IAA Email to Ai Bridges Ltd 22 February 2022”) that the VOR Approach procedure is due for withdrawal by 06 June 2030 according to the State PBN Plan:

*“ VOR RWY 24 IAP: Impact noted and mitigations understood. These are not however consistent with our requirements for SDF etc. If the development goes ahead, I would recommend withdrawal of the VOR IAP on the basis that this would be in line with the State PBN plan and that RNP IAPs are planned for Shannon during 2022 “*

Also as referenced in the State PBN Plan (as shown in Appendix 15-6, section 11 ) the Shannon Airport currently has approach runways are in line for RNP approaches by 25 January 2024:

*“the runway ends that currently have precision approaches, RNP approaches (LNAV & LNAV/VNAV & LPV Minima) shall be established at the same time as the PCP Airports, by 25 January 2024 (phase2).*

This issue can potentially be mitigated through a pre-construction planning condition requiring the Developer to provide appropriate evidence to the relevant planning authority that this new navigation system has been implemented. A specific condition is proposed in Section 6 (as shown in Chapter 15-6 -IFP Safeguarding Knockshanvo Windfarm)

- Air Traffic Control (ATC) Surveillance Minimum Altitude Chart

In their IFP Safeguarding Assessment Cyrrus identify that, there will be an impact to the existing ATCSMAC Charts for Shannon Airport. As part of the ATCSMAC mitigation options presented by Cyrrus, four feasible design options are presented in Annex A of the IFP Safeguarding Report in Appendix 12 that would mitigate the impacts to the ATCSMAC Charts. All of the four mitigation options allow for safe vectoring onto the Instrument Approach procedures, which includes an option for a shortened ILS on an RNP approach. Should Shannon Airport the IAA \ AirNav have any further technical queries in relation to the assessments carried out or the mitigations proposed, the developer would be pleased to address these through a “request for further information”.

### **3.1.4 Summary**

In the concluding statement of IFP Safeguarding Assessment ( as shown in Appendix 12) Cyrrus confirmed that while there are impacts from the proposed development to the Flight Procedures and ATCSMAC Charts at Shannon Airport there are viable mitigation options.

In October 2025 the applicant requested a Teams Call with AirNav to discuss the proposed development so that the potential wind farm impacts could be discussed in further detail (as referenced in Appendix A – Meeting Notes prepared by the Applicant). The Applicant welcomes the update from AirNav Ireland, on this Teams Call, in relation to the IFP redesign process and that the implementation of the PBN plan will reduce the impact on flight procedures as the proposed wind turbines, which will be programmed as obstacles as part of this future re-design. The applicant also notes that AirNav are in the process of carrying out a cumulative impact assessment on the potential wind farm in East Clare, and the minimum altitude sector required to manage flights descending into Shannon and that this can be achieved at the higher altitude of 2400ft.

On this basis the Applicant believes that beyond the PBN implementation date of 6th Jun 2030 that there will be no impact from the proposed development to the re-designed Instrument Flight Procedures for Shannon Airport.

Again the applicant further notes that redesign of the instrument flight procedures scheduled for release in September 2025 has been put back to Q2\Q3 2027. As stated above the applicant would be willing to further engage with AirNav when the redesign of the IFP's are re-designed in Q2\Q3 2027.

The applicant is accepting of the need for financial support. The funding of additional resources that may be required by AirNav to conduct further instrument flight procedure designs as part of their PBN rationalization plan and scheduled Radar Facility upgrades scheduled for 2025 - 2029.

The applicant also accepts that the expectations of Shannon Airport Authority in relation to safe operations, would need to be met i.e. any mitigation measure solution would be safe and ensure an efficient air traffic flow.

As outlined in the Application, the applicant confirms its willingness to contribute its share of the cost of implementing these mitigations (as shown section 5 of the Knockshanvo Wind Farm Aviation Summary Report)

The implementation of the State PBN Plan by 06<sup>th</sup> June 2030 is welcomed by the applicant in the context of building out the proposed development as several of the potential issues identified by AirNav in the detailed assessments noted will no longer be relevant.

As such, proposed turbines T01, T02 and T03 of the Proposed Wind Farm currently noted as penetrating the current departure and approach obstacle protection areas at Shannon Airport however under the new navigation measures, proposed turbines T01, T02 and T03 could be constructed, albeit not until the 07<sup>th</sup> June 2030 when the new measures are rolled out.

The applicant confirms that should ACP deem it appropriate, a planning condition attached to any grant of planning permission issued requiring that turbines T01, T02 and T03 will not be constructed until the measures are in force, is acceptable, in the interests of aviation safeguarding

## 3.2 Radar Surveillance at Woodcock Hill Facility :

The applicant notes the concerns by AirNav and Shannon Airport that the proposed windfarm development would have a significant negative impact on the performance of the radar surveillance systems at the Woodcock Hill facility.

The applicant also notes the AirNav concern that the proximity and scale of the proposed development would lead to radar beam deflections, reflections, and shadowing from the wind turbines and it believes that there are no credible and implementable mitigations that could be applied to the Woodcock Hill radar to eliminate these effects.

The applicant also notes the AirNav concern that the proposed development would compromise the Woodcock Hill radar's compliance with EU mandated surveillance performance criteria required to support 5 Nautical Mile horizontal separation of aircraft in En-Route Irish airspace and 3 Nautical Mile horizontal separation of aircraft in Dublin airspace.

### 3.2.1 Consultations : – Industry Engagements :

The applicant notes that they have been engaging with AirNav ( formerly referred to as the “IAA” ) since November 2021. The details of these consultations<sup>[5]</sup> with AirNav, from November 2021 to April 2022 have been documented and include in the planning submission for the proposed development.

The initial consultation was sent to AirNav in relation to the proposed Violet Hill development, comprising of 18 turbines, as part of a pre-planning assessment. A Radar Assessment against the proposed 18-turbine development, prepared by Cyrrus September 2021, was submitted to AirNav for their review ( Reference 7 )

The AirNav noted the following in their consultation response on 4th February 2022 and stated the following in relation to the Radar Assessment :

*“Methodology of this assessment has been accepted in principle”*

*“While the content of the Radar Assessment is appreciated, the likely costs, operational impacts and timeline deliverables of the proposed wind farm will be need to be further assessed by the ANSP and also in the context of Regulatory requirements.”*

The final consultation response, 22 April 2022, received from AirNav stated that it could not offer its full support, unless the project could consider lowering the elevations of the turbines at this time.

Following these engagements a number of wind farm design changes occurred which ultimately resulted in the site reducing in scale from 18 turbines to the final proposed 9 turbine layout for which permission is being sought Several turbines were removed from the original 18-turbine layout to mitigate impacts on identified constraints which was in part informed by impacts on aviation infrastructure.

On 23 January 2023 the Environmental Consultants MKO sent a consultation, on behalf of the applicant, to the Shannon Airport Authority with the details of the final proposed 9 turbine Knockshanvo Wind Farm development.

On 03 February 2023 AirNav sent a response to MKO, in relation to the proposed development, from the perspective of AirNav as the Air Navigation Service Provider (ANSP) outlining that, there were areas where further analysis would be required.

**Woodcock Hill Radar** :*Surveillance effect (IAA ANSP Surveillance Domain copied). AirNav stated that generally any significant obstacle within 16km of Woodcock Hill Radar facility may have impact. In the case of this proposed development, that an impact would be highly likely and would need to be assessed with mitigations proposed. AirNav noted previous experience*

*has shown that mitigations suggested for similar developments have been prohibitively costly for the ANSP and ultimately don't guarantee that the surveillance service is not affected. AirNav attached a copy of the EUROCONTROL Guidelines on How to Assess the Potential Impact of Wind Turbines Surveillance Sensors.*

On 01 October 2025 an online meeting took place with representatives from AirNav and Radar Safeguarding. The Applicant prepared a brief summary of what they believed were main factual points addressed at this meeting in relation to Radar Safeguarding (as shown in Appendix A ). A copy of these minutes was sent to AirNav on 28 October 2025. These summary points recorded in the Applicant's own minutes in relation to Radar Safeguarding are shown below :

- *AirNav opened with context on the significance of Woodcock hill Radar and how it serves enroute phases of flights and manages significant traffic from the east. Any interference or false radar signals generated by wind turbines can impact operations during these flight phases*
- *Clarification on whether Knockshanvo was part of the Oatfield project was asked or to which project/turbines does this call relate to.*
- *The Applicant showed a map with the Knockshanvo & Oatfield turbines and the number of turbines each project relates to.*
- *The Applicant committed to issuing AirNav with a shapefile of the 9 Knockshanvo turbines.*
- *Concerns were raised by AirNav about radar deflections and false signals caused by wind turbines, which can degrade radar accuracy and safety in controlled airspace, especially beyond 150-250 NM from radar sites. He highlights the lack of evidence supporting coexistence of large wind farms and radar operations without adverse effects. Aviation authorities are not permitted to degrade radar safety standards, and any mitigation must be proven not to compromise operational safety. This reflect the only remaining issue.*
- *Potential mitigation includes upgrading radar systems or installing additional radar sites to maintain coverage and safety. There are, however, the complexity, cost, and technical challenges of such upgrades, for radar equipment and infrastructure, with ongoing maintenance expenses. Alternative technologies like wide-area multilateration were considered but found suboptimal for the region's unique geography*
- *AirNav expressed openness to reviewing evidence from developers or consultants demonstrating radar coexistence with wind turbines, at distances of 150NM – 250NM. Ideal evidence would include radar data screenshots showing no adverse deflections within safeguarding zones.*

The applicant became aware of a report that was drafted, in July 2025, by AirNav that addressed the issue of deflections in relation to the Woodcock Hill Radar ( as referenced in relating to an Telecommunications mast which is in line of sight with the Radar. This issue was openly discussed during a meeting involving representatives from the Department of Transport, AirNav, Wind Energy Ireland and Renewable Energy Ireland which was documented ( as shown in Appendix B ). An extract from this meeting showing the concerns that AirNav in relation to the deflections while also noting that this was the only remaining issue of concern in relation to the Woodcock Hill Radar. AirNav conclude by stating that they require evidence or case study examples that wind turbines deployed within comparable ranges ( as the developments in East Clare and currently in planning ) and in view of an En-route secondary radar have not impacted the surveillance performance of that radar. AirNav require this evidence in line with test and validation evidence for AirNav and IAA regulatory approvals. AirNav state that they have communicated this requirement for in-service evidence in all meetings with the Wind farm developers. AirNav state that radar deflections, reflections and shadowing by wind turbines within the safeguarding zones all remain a concern

### 3.2.2 Technical Assessments

#### Cyrrus Radar Assessments :

In 2025 the Applicant engaged Cyrrus to review the impacts of the proposed development consisting of 9-turbines on the Radar Surveillance equipment at Woodcock Hill. The review was carried out against Eurocontrol Guidelines as requested by the ANSP. The initial radar assessment<sup>[13]</sup> of the potential impacts of the proposed development was completed in December 2023. Following the request by AirNav for more evidence, Cyrrus incorporated the necessary evidence in the form of updates in a revised assessment (as shown in Appendix C).

In their Radar Mitigations Options Study, Cyrrus conducted a detailed technical assessment with detailed calculations and analysis showing there would be no **shadowing effect** caused by the proposed development on the Woodcock Hill Secondary Radar. This is addressed by way of an update (as shown in Appendix C – Section 5.6 to 5.8) where a cumulative assessment of the shadowing impact of the proposed development and the Oatfield development, which is also in planning.

Figure 1 below shows that there is vertical coverage even when taking the highest wind turbine T03 as listed in the Cyrrus Safeguarding Report CL-6005- RPT-003 v2.0, and the calculated height of shadowing, Figure 15 shows that shadowing does not infringe the required MVA of 2,300ft for aircraft flying in instrument flight rules.

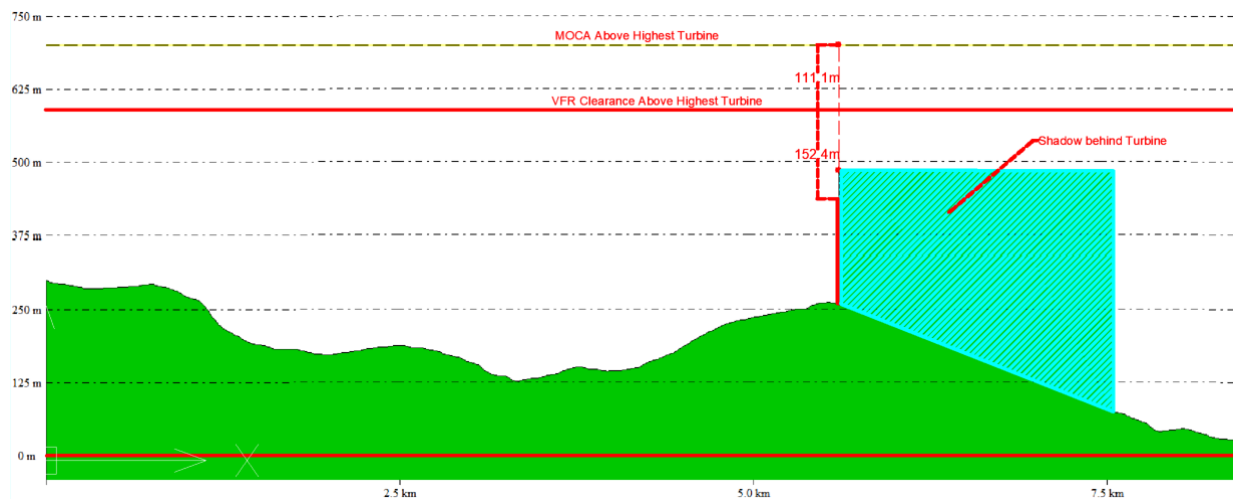


Figure 1: Radar Line of Sight with wind farms shown in blue together with minimum radar surveillance coverage at 2,300ft is maintained

Figure x demonstrates that to determine the horizontal shadow areas, lines of the dimensions modelled ( as shown in Appendix C, section 5.7) are overlaid on Google Maps™. The shadow areas are very thin being only 46m wide. Consequently, the probability of loss of SSR returns over the wind farm is minimal. Eurocontrol defines a 'Loss' as being failure to detect two or more target positions. This definition is used by most ANSP's in their Surveillance System Safety Cases. The crossing direction of the aircraft also impacts this probability. Therefore, with the probability of an aircraft position being exactly on two consecutive shadow areas is very unlikely to occur. From this it could be concluded that any potential Operational impact to ATC should be acceptable.

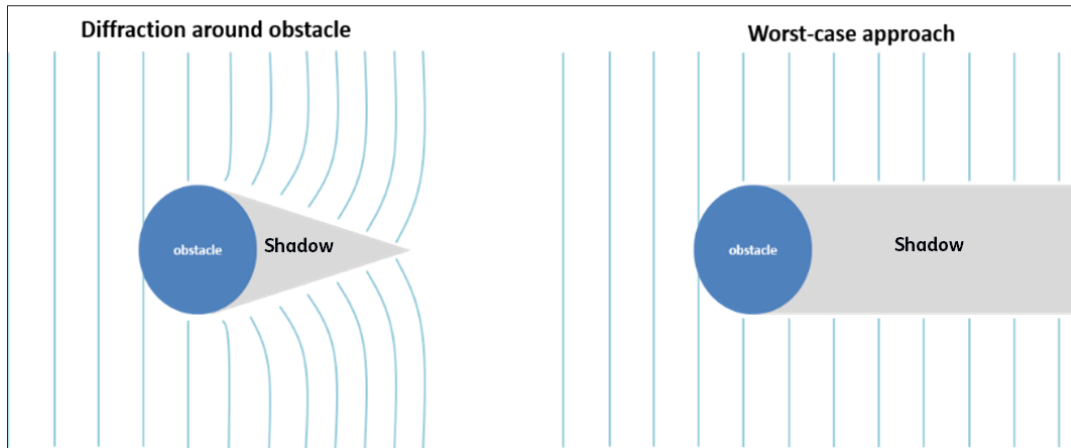
Cyrrus also address the common concern is the 'cumulative effect' whereby individual wind farm developments would not be a problem for Air Traffic Service providers, but together they have an impact. The nearest development to Knockshanvo Wind Farm is Oatfield Wind Farm. Applying the same methodology for this development results in the surveillance coverage shown in Figure 2. The areas of poor detection are shown as red lines of 2Km length and just 30m wide.



Figure 2 Woodcock Hill MSSR cumulative Shadow areas by the Knockshanvo Turbines combined with the Oatfield turbines

Cyrrus also reference the Radar Assessment that they conducted in 2021 ( Chapter 15-6 – Violet Hill Wind Farm Radar Assessment) against previous 18-turbine design and state that this turbine design did not cause any significant adverse shadowing affect and that the shadowing effect of the reduced 9-turbine design would be no worse.

It should be noted that TNO also address the matter of **shadow effects** in the case when a wind turbine in the line-of-sight path will affect visibility, but not in all cases will it cause the target to be invisible. Radio waves diffract around an obstacle, limiting the shadow zone directly behind an obstacle. Because energy is reflected back from the wind turbine the presence of a wind turbine will cause a loss in maximum detection range. TNO go on to state that because the power budget between the target aircraft transponder and the MSSR interrogator is commonly high, detection loss is normally not observed. At maximum range, typically, other MSSRs take over where there is duplicated radar coverage. Figure 3 below is a graphical illustration that shows shadow effects behind an obstacle by diffraction methods and the experimental computer modelling method showing worst case when real-world data is available to discount over-reliance on assumption



**Figure 3 Shadow effects behind an obstacle by diffraction methods and the experimental computer modelling method**

In relation to the common issues relating to wind farm impacts on Radar Surveillance Systems, Cyrrus also note that in relation to the issue of Reflections, that the Radar at Woodcock Hill is a Thales RSM970 MSSR and is sited 5.6 km from the nearest wind turbine. The Thales radar utilizes a two-stage system to prevent both temporary (Dynamic) and permanent (Static) reflections being displayed. It also has inbuilt adaptive reflection processing. To prevent possible reflection issues, some minor optimization may be required. This is usually carried out as part of the scheduled maintenance of the equipment. On the issues of Deflections the Thales RSM970 MSSR uses a well-established processing system to remove any False Replies Unsynchronized In Time (FRUIT). This process removes the issue of deflections from the system. No additional optimization is required as a DEFRUITER is part of the standard MSSR processing on the Thales system.

**AirNav – Surveillance Description of Woodcock Hill Radar Signals Deflections :**

The applicant also became aware of the report that was prepared by AirNav and which specifically related to the issue of deflections impact on the Woodcock Hill MSSR Radar caused by a telecoms mast 730m away. It showed the impacts of radar deflections at the maximum instrumented range of 256NM of the Woodcock Hill MSSR ( as referenced in Appendix H – Surveillance Description of Woodcock Hill Radar Signal Deflections ).

**TNO - Detailed Engineering Assessments :**

Following the industry engagements that took place in July 2025 and their engagement with AirNav in October 2025, the applicant commissioned Ai Bridges to engage with TNO, an independent research organization in the Netherlands who have the software tooling capabilities to simulate and report on the effects of tall buildings, structures or wind turbines on radar systems. TNO carried out a Detailed Engineering Assessment (DEA) against the potential impacts of the proposed development on the MSSR at Woodcock Hill. A line of sight analysis and coverage maps were generated and the Off Bore-sight Error (OBE) so the error in the detection angle of the MSSR with respect to the actual target position could be calculated. The DEA considered three scenarios across the target’s heights of 5000ft, 7,000ft, 10,000ft and 35,000ft for :

- the coverage for the existing baseline of the already consented wind farms in East Clare ( Lackareagh, Fahy-beg and Carrownagowan wind farms )
- the coverage for the proposed Knockshanvo wind turbines along with the already consented wind farm turbines
- the coverage for the proposed Knockshanvo wind turbines, the already consented wind farm turbines and the proposed Oatfield wind turbines which is also in the planning system.

The TNO DEA Assessment which was completed in January 2026 and the applicant has presented to AirNav for their review. Following their review of the TNO Assessment, AirNav have reverted to the applicant with a request for a further meeting to discuss the findings of the Assessment Report.

The outcome of the TNO modelling has been used by ANSP's in other EU Member States to assist with determining if the deflection impacts caused by wind turbines on MSSR are operational acceptable and in other cases the DEA reports inform an appropriate mitigation scheme.

### **TNO – Case Studies :**

The Applicant, on foot of the recent significant information received in relation to AirNav's radar sensors in operation in the State, commissioned Ai Bridges to engage TNO to conduct further DEA assessments and prepare Case Studies to obtain evidential support and specific evidence by way of simulations that will substantiate the evidence and concepts contained within the Radar Mitigations Options Study prepared by Cyrrus .

The applicant also re-engaged Cyrrus to update their Radar Mitigations Options Study prepared in December 2023 to address the operational considerations in the context of Eurocontrol Surveillance Standards which defines the surveillance requirements for aerodromes and terminal areas as applicable for Shannon Airport (as referenced in section Appendix C, section 5.3). which was completed on 15 April 2026.

The Applicant believes that the mitigation options are credible and that they can provide a simulation model that quantifies empirically the exact level of impacts that may be caused by the proposed development on the Woodcock Hill MSSR.

### **3.2.3 Mitigation Options**

It was reported in the Radar Mitigations Option Study that while there would be impacts on the Secondary Radar (MSSR) at Woodcock Hill, these impacts would be operationally tolerable and mitigations are called out in the "Radar Issues and Mitigations Solutions" (as shown in Appendix C, Table 2).

Cyrrus have conducted their initial radar safeguarding assessment in 2023 stating that there are credible and implementable mitigation measure solutions. Following the submission of AirNav and Shannon Airport, Cyrrus revised and updated their Radar Mitigation Options Assessment (as shown in Appendix C) in 2026 to provide the detail on the Woodcock Hill MSSR radar systems and the likelihood of compliance with the Operational Requirements in the presence of the proposal development i.e. namely ability of the system to be able to support APP minimum separation of 3NM horizontal separation and ACC minimum separation of 5NMin line with EUROCONTROL requirements. Based on the detailed technical assessments, the mitigation measures required to address any concerns in relation to radar facilities relates to the Woodcock Hill Secondary Surveillance Radar have been provided for review by AirNav. To prevent possible deflections issues, Cyrrus have some highlighted optimization of the existing radar system may be required. Cyrrus state that the erection of the 9-turbines would have no operational impact on the Woodcock Hill MSSR system and should the Woodcock Hill Radar require optimization this would be completed one channel at a time and allow the system and allow the system to remain operational throughout. Cyrrus also recommend an asset condition survey of the Woodcock Hill Radar system be undertaken by Thales (the manufacturer and Design Authority of the radar system). If upgrades or optimization are required to the Woodcock Hill Radar system transitional arrangements can be managed to ensure minimal operational disruption occurs.

In addition to the Radar Issues and Mitigations Solutions section within their assessment, Cyrrus also provide a suite of 4 mitigations options

**Option 1 – Upgrade existing MSSR.**

*The existing MSSR could be replaced with MSSR system with suitable wind turbine mitigation. However, the mitigation is unlikely to resolve the concerns raised by AirNav Ireland relating to deflections. As Cyrrus do not believe these are caused by the MSSR itself, but it's implementation in the wider Surveillance System i.e. AirNavs Multi Radar Tracker using the MSSR beyond Eurocontrol's recommended limits [2].*

**Option 2 – Short range supplementary MSSR.**

*As a supplementary MSSR would only need to provide coverage over Knockshanvo, equipment with less than 20NM would be more than adequate if sited correctly. Furthermore, with a range of less than 30NM it would cover adjacent windfarms and possibly those proposed for the future. This mitigation solution would require the new MSSR to be integrated into the AirNav MRT. If this is not accepted, other equipment could be installed to integrate the existing and new MSSR by providing combined data for use by Shannon Airport (No impact to En-Route Upper Airspace).*

**Option 3 – Supplementary MSSR with extended range.**

*While a supplementary MSSR with the normal equipment capability to provide 250NM coverage, at this range the antenna rotation rate would need to be slower. Consequently the 'update rate' would be non-compliant with Eurocontrol [3]. However, extending the distance to 80NM may be feasible, this would provide betterment to the existing AirNav Surveillance System.*

**Option 4 – Wide Area Multilateration.**

*While WAM could provide a solution for Knockshanvo and other proposed windfarms, AirNav has stated this would not be acceptable.*

TNO, have listed examples of mitigation measures examples in the PERSEUS Overview document (as shown in Appendix E – Mitigation Measure Examples, pages 16 to 27) which shown below

**Option 1 - Radar fusion of data from multiple radars, e.g. ATM surveillance Tracker And Server ( ARTAS ) of EUROCONTROL, combined with additional radars**

**Option 2 - Realisation of additional radars including in-fill radars**

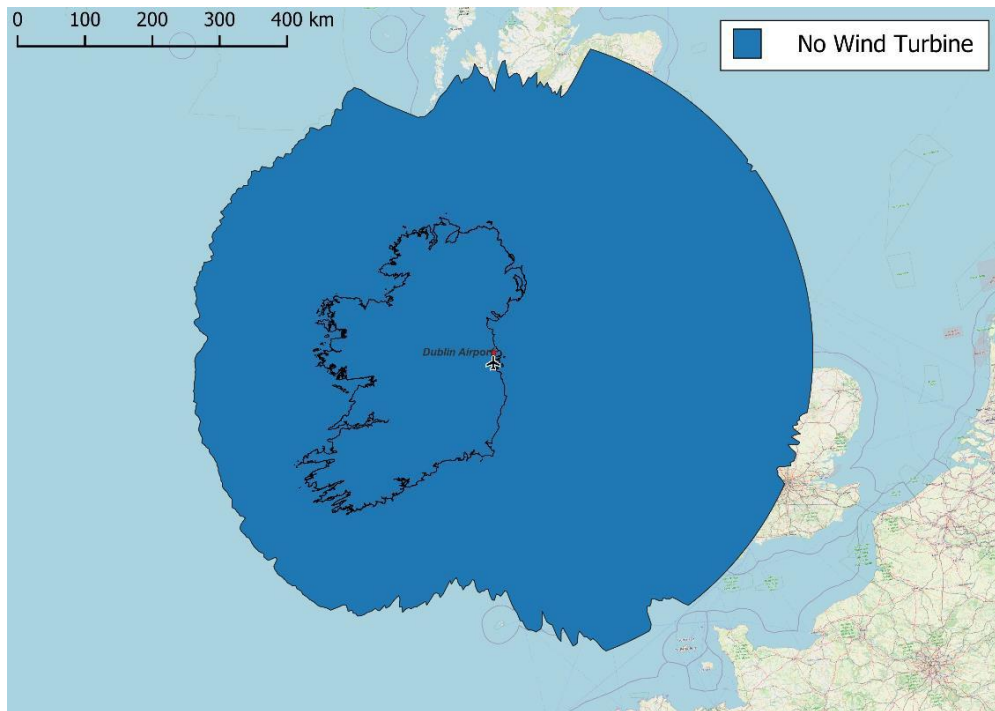
**Option 3 - 3D radars instead of 2D radars**

**Option 4 - Processing improvements within the radar**

TNO, in their DEA for the Australian Case Study ( as shown in Appendix I, Section 8 ) lists the potential mitigation measure solution which was implemented in Australia and involved combing or fusing tract and plot data from multiple MSSR sensors. In the case of the case study that has been presented by TNO the Mount Bobbara, Majura and another already existing MSSR at Mount Macedon was the mitigation measure solution that was implemented. At a target altitude of 20,000ft and higher the MSSR at Mount Macedon provides full coverage over the areas where the off-boresight error effects due to the windfarm were seen. This satisfied the operational effects of the ANSP which was to provide En-Route radar surveillance coverage.

TNO refer to the use of another MSSR as a possible mitigation to provide duplicate coverage In the Knockshanvo DEA ( as shown in Appendix G, Section 4.5 ). The DEA of the Woodcock Hill MSSR shows that wind turbines within the surveillance area introduce some degradation, expressed as an increased Off Boresight Error for targets across the instrumented range and at various altitudes. These performance losses indicate that the wind turbines could potentially interfere with the precision of the MSSR in specific areas. To assess potential mitigation, the coverage of a second En-Route Mode-S MSSR within the State, the combined PSR and MSSR Tooman, was estimated under the

assumption of an undisturbed environment (i.e., assuming that there are no wind turbines in Line-of-Sight of the MSSR). TNO provide the service coverage for the Tooman MSSR radar for targets at altitudes of 5,000 feet, 7,000 feet, 10,000 feet, 10,000 feet and 35.000 feet ( as shown in Appendix G , Section 4.5 Figures 4.38 to 4.41) with the Line of Sight Coverage diagram at the target height of 35,000 feet AMSL as see from the MSSR radar at Tooman shown in Figure 4.



**Figure 4 Line-of-Sight coverage diagram for a target at 35000 ft AMSL as seen from the Tooman MSSR**

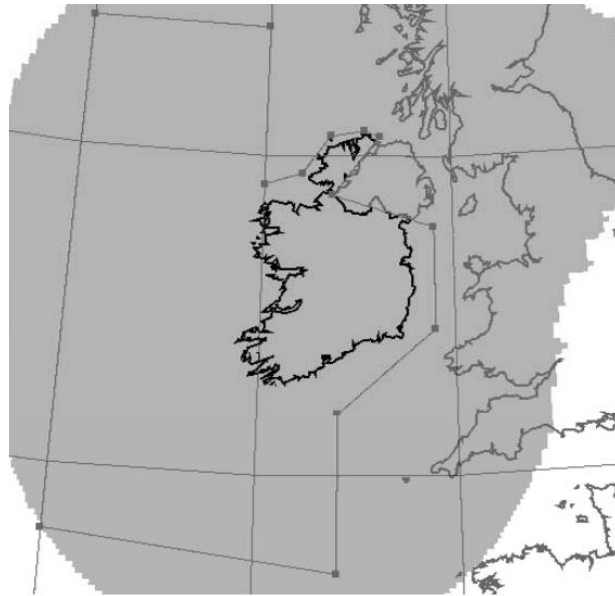
Both Cyrrus and TNO in their assessments refer to ARTAS (ATM suRveillance Tracker And Server), which is a system designed by Eurocontrol to operationally support Aerial surveillance and Air traffic control by establishing an accurate Air Situation Picture of all traffic over a pre-defined geographical area) and then distributing the relevant surveillance information to a community of user systems. ARTAS is a distributed system composed of a number of identical subsystems co-operating together. Each subsystem, called an ARTAS Unit, will process all surveillance sensor data to form a best track estimate of the current Air Traffic situation within a given Domain of Interest. Adjacent ARTAS Units co-ordinate their tracks to build a unique, coherent and continuous Air Situation Picture over the complete area.

The AIP's were referenced to understand the secondary surveillance coverage for the State according to ENR 1.6 Radar Services and Procedures<sup>[18]</sup>. The service coverage is shown in Figure x below. The ENR 1.6 AIP was referenced online and the revision that is available is dated 11 August 2022. The reference to the SSR coverage is shown below. In Figure 5

**SSR Service**

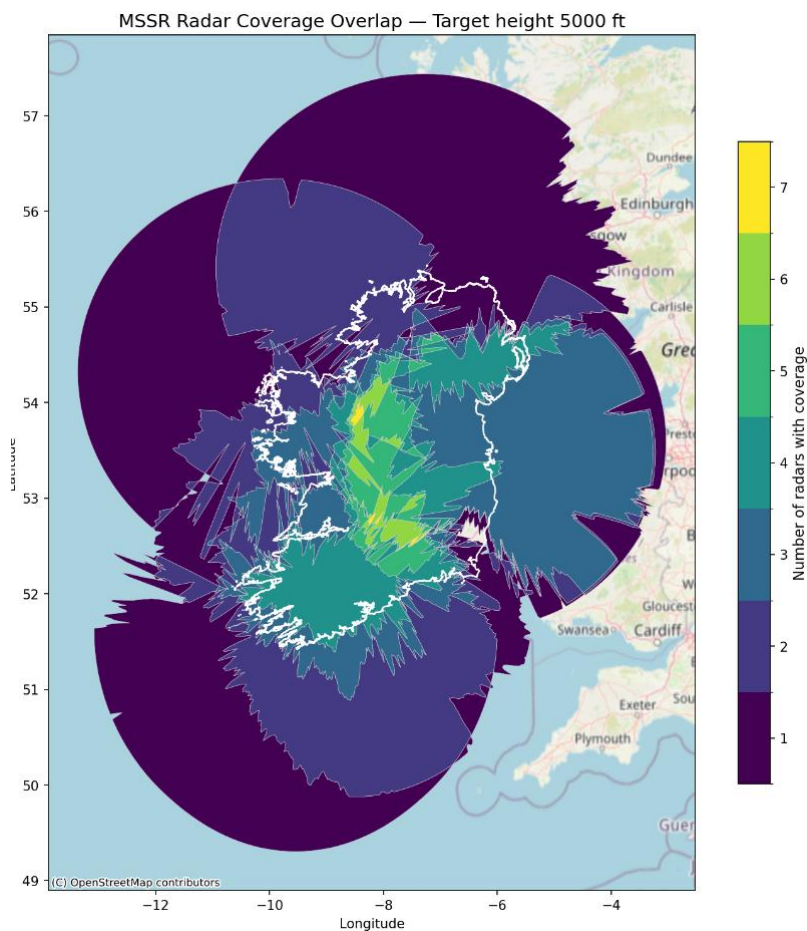
*Radar service is provided in the Shannon FIR/UIR in accordance with procedures specified in ICAO DOC 4444 – ATM 501/15 as supplemented by ICAO Regional Procedures.*

*The airspace within which radar services may be provided comprises those parts of the Shannon FIR/UIR within range of the Shannon, Dublin (3 Stations), Mount Gabriel (2 Stations), Cork, Woodcock Hill, Malin and Dooncarton MSSR stations.*

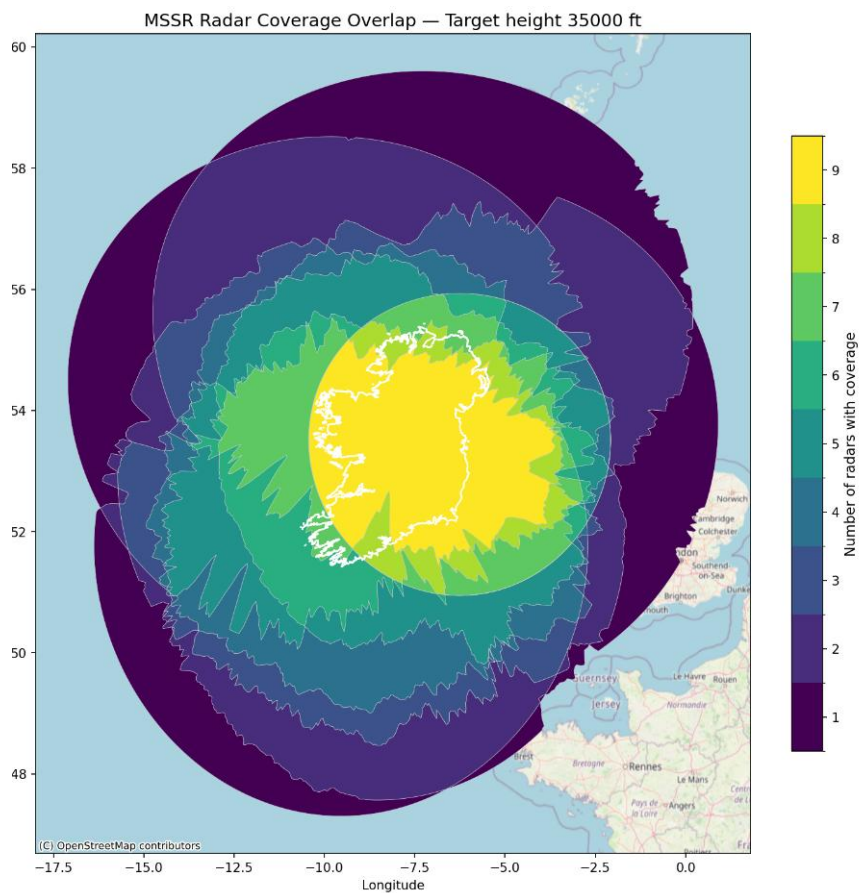


**Figure 5 ENR 1.6 Radar Services and Procedures - Graphic portrayal of area of SSR Coverage**

In order to better understand the overlapping coverage of all of the individual surveillance sensors the radar coverage maps were plotted. The service coverage for all of the secondary surveillance sensors was plotted at altitudes of 5,000ft AMSL and 35,000 feet AMSL. In figures 6 & 7 below show secondary surveillance radar coverage that feed into the multi-radar tracker.



**Figure 6 The combined coverage map from all SSR with the number of radars covering a specific area at 5000 feet altitude AMSL (Average Mean Sea Level) showing colour coded overlapping coverage**



**Figure 7** The combined coverage map from all SSR with the number of radars covering a specific area at 35000 feet altitude AMSL (Average Mean Sea Level) showing colour coded overlapping coverage.

### 3.2.4 Summary

In addressing the shadowing issue both Cyrrus and TNO state that shadowing will not be a significant issue and Cyrrus call out radar optimisations or radar adaptations that can be implemented should then be required.

Cyrrus also address the issue of reflections and point out that the RSM970 MSSR Radar at Woodcock Hill has inbuilt adaptive reflection processing and uses a two-stage system to prevent both temporary and permanent being processed.

Cyrrus, in their Conclusion within the Radar Mitigations Options Study , recommend

*Timescales for the upgrade of the Shannon Airport PSR with co-mounted SSR should be provided by AirNav to clarify if an interim upgrade is required to the STAR2000.*

*Timescales for the planned upgrades to the Woodcock Hill radar system should be provided by AirNav to clarify if an interim upgrade is required to the RSM970.*

*As the manufacturer and Design Authority, AirNav could request that Thales assess the type of Mitigation package required and that they will confirm costs and timescales based on their scope of work.*

Cyrrus reviewed the independent Detailed Engineering Assessment completed by TNO, based on a validated assessment methodology, which completed to Eurocontrol Guidelines. Cyrrus note the AirNav claim in relation objection to the proposed development

*“This development would compromise the Woodcock Hill radar’s compliance with EU mandated surveillance performance criteria required to support 5 Nautical Mile horizontal separation of aircraft in En-Route Irish airspace and 3 Nautical Mile horizontal separation of aircraft in Dublin airspace.”*

Cyrrus state

*“The TNO Report supports the Cyrrus findings as it shows that the potential impacts from the Knockshanvo wind turbines does not occur over Dublin Airspace but to the North East of the country.”*

Cyrrus also note that the TNO assessment indicates that another existing MSSR (i.e. **Tooman**) **provides overlapping coverage with Woodcock Hill MSSR thereby ensuring redundancy within the ARTAS multi-radar tracker system and maintaining surveillance performance.** This is in line with the Cyrrus view that the network of MSSRs across Ireland provides redundancy in the air coverage and using the ARTAS system. There is no expected reduction in surveillance performance required to support both the 5NM

### **3.3 Previous Developments since 2018 :**

The Applicant also notes the AirNav concern that since 2018 there have been previous engagements relating to a number of other developments across the footprint of the Knockshanvo site and that AirNav have maintained their objections to all of these proposed developments

In their consultation response in January 2023 AirNav refer to “previous experience” in relation to “similar developments”. The details of the previous developments that have been reviewed for the same site at the proposed Knockshanvo Project have been included below :

- Brookfield Renewable pre-planning development in 2018.
- Coillte pre-planning development at the Violet Hill site in 2020 – 2022.

There was extensive stakeholder engagement to discuss the outcomes of the above projects, both of which have informed the baseline assessment of the Knockshanvo Project. The stakeholders involved were the AirNav, Shannon Airport Authority, the wind farm developers and several aviation specialists contracted by the developers.

In 2018 a wind farm development was previously proposed by Brookfield Renewables (hereafter referred to as “Brookfield”) for 26 turbines which went through a pre-planning cycle. This development was proposed at the same location as the proposed Knockshanvo Project. The initial consultation with the IAA for this previous development was in 2008 regarding a meteorological mast. At that time the IAA stated that an objection would be raised against any future wind farm planned for the site. Brookfield engaged with the IAA from 2016 – 2018 and several detailed technical assessments were carried out at the request of the IAA. Brookfield contracted aviation specialists to conduct specialist Instrument Flight Procedures and Radar Assessments respectively.

In 2018 Brookfield also contracted the National Air Traffic Services (NATS) to conduct a Technical Safeguarding Summary against said assessments. (NATS is UK's principal air navigation services provider which provides air traffic management services to aircraft within UK airspace). On the matter of the Woodcock Hill Radar assessment, NATS noted that the Radar Assessment, derived from EUROCONTROL GUIDELINES, was very similar to the process that NATS themselves use to safeguard their own Secondary Radars across the UK. NATS also noted they were unable to comment on the conclusion in the Radar Assessment that “aircraft would be unlikely to fly within the shadow” without input from the IAA ANSP or Shannon Airport Authority but that the conclusion does not seem unrealistic given the low altitudes of shadow regions indicated in the report.

The reference by AirNav to “Violet Hill” is a reference to the proposed 18-turbine Violet Hill development that was considered for the same site as the Knockshanvo Project from 2020 to 2022 as part of a pre-planning assessment. This has already been discussed above and the details of the engagements with the AirNav have been included in the planning submission ( as referenced in Appendices 1.1 to Appendix 9 )

### **3.4 Navigational Aids**

The Applicant notes that there was no specific objection or concern raised by either AirNav on Shannon Airport in their submission in October 2024 in relation to any adverse effects of the proposed development may have on the Flight Inspection Procedures and profiles associated with the Shannon Airport Runway 24 Instrument Landing Systems.

### 3.4.1 Consultations

On 01 October 2025 an online meeting took place with AirNav and IFP's were discussed. The applicant provided a summary of the specific points discussed in relation to IFP's as part of the applicant's own meeting minutes ( as shown in Appendix A) A copy of these minutes were sent to AirNav on 28 October 2025. The summary points in relation to the IFP's are shown below

- *Redesign of the IFP's scheduled for release in September 2025 has been put back to Q2/Q3 2027,*
- *The implementation of the PBN plan will reduce the impact to flight procedures and the potential as the obstacles have been programmed.*
- *AirNav are in the process of carrying out a cumulative impact assessment with FCSL on the potential wind farm in East Clare, and the minimum altitude sector required to manage flights descending into Shannon. This can be achieved at the higher altitude of 2400ft.*

In August 2021, the Applicant previously commissioned FCSL, an IAA approved service provider, to conduct an assessment against the 18-turbine layout. The findings were that ILS flight inspection procedures would potentially be impacted and the procedures would have to be flown at an increased height which could result in an increased flight inspection costs. FCSL recommended that flight trials be conducted to ensure correct ILS received operation at increased ranges. Following additional flight trials, FCSL confirmed that adequate signals were received when the flights were conducted at 2,600ft and 3,000ft. FCSL confirmed that when the flight inspection operations are conducted in instrumented metrological conditions at 2,7600ft and the 18-turbine layout would not have any effect on the Shannon Airport Runway 24 flight inspection procedures. The summary sections from each of the FCSL assessment are include below ) details of which contained in Appendix 15-6 and referenced below

#### **FCSL Assessment – August 2021<sup>[7]</sup>**

##### **Assessment Summary :**

*Flight inspection aircraft flying centreline, part orbit and bottom edge flight profiles associated with the Shannon Airport Runway 24 ILS would remain sufficiently clear of the proposed Wind Farm Site.*

*The ILS slice and left slice 8° profiles, the proposed wind farm will require that these profiles are flown at higher altitudes to provide sufficient clearance above the proposed wind turbines. The flight inspection Glide Path left slice 8° profile (level run) will have to be raised to an altitude of 2,600ft in IMC to provide the flight inspection aircraft adequate coverage over the proposed wind turbines. This will result in increased flight inspection costs for the extended Glide Path level runs. If there is insufficient Glide Path RF signal for the extended level run at 2,600 ft then it may not be possible to conduct this flight inspection in conditions of bad visibility. This may result in additional cost if the flight inspection aircraft is delayed while waiting for VFR conditions.*

##### **Assessment Recommendations :**

###### *Flight Trials*

*Additional flight trials should be conducted at the next routine ILS flight inspection to assess the RF signal levels for an extended level Glide Path run at an altitude of 2,600 ft.*

###### *ILS Computer Simulations*

*The proposed Violet Hill Wind Farm site is within the Shannon Runway 24 Localiser lateral coverage sector (see Figure 3.3 above).*

*As the proposed Violet Hill Wind Farm site is within 8° azimuth and 1.3° elevation of Localiser antenna boresight, there is potential for the proposed wind farm to cause interference to the Runway 24 Localiser guidance signal at ranges of between 10 NM and 25 NM from the Localiser antenna. It is recommended that computer simulations be performed to assess the levels of potential interference to the Runway 24 ILS Localiser guidance signal.*

### **FCSL Assessment – April 2022<sup>[10]</sup>**

#### **Assessment Summary :**

*The results of the special Glide Path flight inspection presented in section 3 above show that, with the exception of the right slice 8° profile flown at an altitude of 3,000 ft, adequate Glide Path RF signal levels were received at the higher slice (level run) altitudes of 2,600 ft and 3,000 ft. Adequate fly-up guidance was achieved below the Glide Path sector for all level run profiles flown.*

*This means that if ILS flight inspection operations are conducted in IMC, the flight inspection level runs can be flown at 2,600 ft and the proposed Violet Hill wind farm will therefore not have any adverse effect on Runway 24 ILS flight inspection procedures and flight profiles. If a replacement Runway 24 ILS is to be commissioned at Shannon Airport at some time in the future, commissioning flight inspections will be conducted in VMC, so the proposed Violet Hill wind farm will therefore not have any adverse effect on future ILS commissioning flight inspection procedures and flight profiles*

## 4. Evidential Support - Case Studies :

At the meeting with AirNav on 01 October 2025, examples and case studies were called for in order to demonstrate where there evidence of existing wind farms that operate in proximity to an operational surveillance radar ( vendor-agnostic and mode-agnostic would be acceptable ) and where there were no operational impacts to the radar performance.

At this meeting it was highlighted that there was examples of operational wind farms in the Republic of Ireland that were located inside the 16km wind farm assessment zone assessment , as prescribed by the EUROCONTROL Guidelines that are issued on how to assess the impacts of wind turbines on radars.

At this meeting the Applicant committed to working with Air Nav and Shannon Airport Authority to clearly identify the impacts which are likely to occur through modelling in an empirical manner and to identify an optimum mitigation solution should this be required. To this end, the Applicant commissioned Ai Bridges to engage with TNO, who have conducted a series of detailed engineering assessments and Case Study Reports that demonstrate that the impacts of wind turbines on MSSR can be accurately modelled and that this modelling has been used to assist ANSP's with mitigation measure solutions. The following candidate references below and a description of each is referenced below

- Schiphol Airport Case Study – TNO Modelling Validation
- Detailed Engineering Assessment – Wind Turbines at Knockshanvo
- Boolynagleragh Wind Farm – Shannon Secondary Radar Combined with Boolynagleragh
- Australian Case Study – Australia MSSR Radar Assessment
- Woodcock Hill MSSR – Radar beam Deflections Modelling

### 4.1 Schiphol Airport Case Study – TNO Modelling Validation

Engagement with TNO in relation to the proposed development began in November 2025. There were extensive discussions with TNO to confirm that they could deliver on the scope of requirement set out by AirNav. TNO confirmed that they were able to conduct a Detailed Engineering Assessment to model the extent of the impacts of the proposed development on the radar performance of Woodcock Hill MSSR specifically in relation to the deflections issue

A background to the TNO company profile, the team, tooling capabilities, experience along with international precedents and the validation of their PERSUES software tool has been provided below.

The TNO research and work on the effects of wind turbines including deflections and shadowing issues has been used internationally by Air Navigation Service Providers and Wind Farm Developers and also informed updates of National Regulation in another EU State.

**TNO Company Profile :** TNO is a not-for-profit organisation established by law in the Netherlands. They have more than 30 years' experience in modelling the effects of wind turbines on Defence radars and develops assessment methods since 1995. TNO has been sponsored by the Netherlands Ministry of Defence and Ministry of Economics to develop a modelling tool, PERSEUS, specifically TNO have developed the PERSEUS tooling capabilities for primary and secondary radar simulations. The TNO team comprises 80 people working across all service divisions.

**TNO Company Radar Assessment Team** : The following team contributed to the preparation of the Detailed Engineering Assessment for the Knockshanvo proposed development ( as shown in Appendix G )

Onno Van Gent : Former Program Manager, currently part-time role and who has more than 25 years' experience working at TNO as a Radar and Electronic Warfare engineer. Onno also has over 15 years' experience in radar performance dues to wind turbines and other obstacles

Duije Deurloo : is the Current Program Manager with more than 25 years working at TNO as Radar Front-End.

Detmer Bosma : More than 5 years working at TNO as a Radar Expert and 2 years performing Radar interference studies due to wind turbines

**TNO Capability Statement & International Precedent** : TNO takes the formal role within the Netherlands in assessing each wind turbine above a certain turbine tip height. TNO also provide consultancy services to support the Dutch government and Civil Air Control. The TNO PERSUES modelling tool identifies potential issues with wind turbine interference and assist mitigation measures. In Belgium TNO have performed studies for Skeyes ( the Belgium ANSP ) to update national regulations. TNO have also supported wind farm developers in Belgium, Denmark, Finland, Sweden, France, Switzerland, Malta, United Kingdom & NI and Australia

**TNO PERSEUS Modelling Validation** : TNO were requested to show the how they validated their PERSEUS Tooling Capabilities and demonstrate how their modelling software could be used to accurately model the effects of wind turbines within proximity of 2km from a MSSR radar.

TNO presented an example at and Air Traffic Control tower that is located 1.9km – 2km north of the MSSR Radar (RSM970S) Brussels Airport. The ATC tower can be seen in Figure 8.



**Figure 8 ATC Tower at Zaventem Airport ( Brussels)**

TNO demonstrated that they modelled the track error effects of the ATC tower on the MSSR at Zaventem Airport (Brussels) which can be seen in Figure 9 below, which shows the recorded real track from ATC at approximately 200km TNO use the PERSEUS tool simulate the worst-case

scenario effects of the ATC tower, as shown in Figure 10 which can be seen to accurately model the of simulated track real-world effects of the ATC tower on the MSSR radar service coverage



Figure 9 : Recorded ATC real track at approximately 200km as seen by the Air Traffic Controller on Radar screens

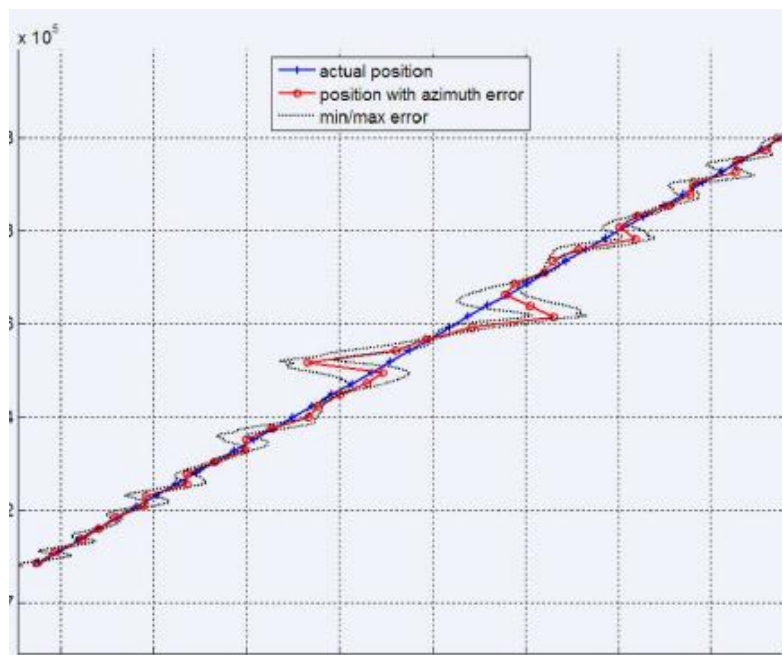


Figure 10 : TNO PERSEUS Model Simulated Track which shows a very high degree of accuracy

### Deflections Modelling :

TNO have developed their own method of modelling bearing errors associated with of radar beam signals based on the work of L. Vinagre and K. Woodbridge and published a paper<sup>[19]</sup>. TNO have used this modelling method and applied this to the modelling of bearing errors associated with deflections caused by wind turbines. Their modelling is based on the Eurocontrol Guidelines on assessing the potential impact of wind turbines on surveillance radars

A summary of the modelling approach that has informed the TNO modelling has been provided

*estimate the azimuth error curve due to obstacle shadowing based on cylindrical diffraction theory is described and a comparison between measured data and the estimated error curves reveals that bearing errors can be very precisely calculated.*

The method developed by Vinagre and Woodbridge shows that it has been developed in the interest of safeguarding of secondary surveillance radars. The modelling method, at the time it was developed, estimates the bearing errors caused by telecoms masts, buildings and radome structures. The method has been validated using real data of a MSSR radar which was partially obstructed by a metal telecoms mast of width 2m at a range of 600m from the MSSR. An extract from the paper is included below.

*recorded data from some secondary surveillance radar (SSR) stations has shown deviations positional accuracy when the SSR antenna shadowed by neighbouring man-made structures (such as communication masts, buildings and radomes). Modern SSR monopulse receivers estimate the azimuth of aircraft through the orientation of the incident planar wavefront. Obstacles in the propagation path diffract part of the electromagnetic wave energy and as a result, the electric field across the antenna array is subject to a disturbance. The resultant azimuth error in the shadowed sector depends on the width and height of the obstacle and on its position relative both to the radar and the aircraft. A method to estimate the azimuth error curve due to obstacle shadowing based on cylindrical diffraction theory has been developed. A comparison between measured data and the estimated error curves reveals that bearing errors can be very precisely calculated. Accurate estimation of azimuth errors due to obstructions has increasing significance for operators of SSRs. Radar performance must continue to be safeguarded in the face of increasing pressure to allow development on or near radar sites. Methods of estimating the effects of such developments will play a key role in future safeguarding.*

Additional research was also completed by Vinagre and Woodbridge and was conducted in the interest of safeguarding of secondary surveillance radars. The research was conducted specifically in relation to the modelling and prediction of obstacle shadowing on secondary surveillance radar target azimuth on 20 secondary surveillance radar (SSR) radar stations operating in the UK, dating back to 2002

*National Air Traffic Services Ltd. (NATS) currently operates some 20 secondary surveillance radar (SSR) stations throughout the country for monitoring air traffic. Recorded data from some of these sites has shown deviations in aircraft positional accuracy when the SSR antenna is partially shadowed by neighbouring man-made structures. Modern SSR monopulse receivers estimate the bearing of aircraft through the orientation of the incident planar wavefront. Obstacles in the propagation path diffract part of the electromagnetic wave energy and as a result, the electric field across the antenna array is disturbed. The resultant azimuth error in the shadowed sector depends on the shape, distance and relative height between the antenna and the shadowing obstacle. A method to predict the azimuth error curve due to obstacle shadowing based on cylindrical diffraction theory is described. A comparison between experimental and calculated data reveals that azimuth errors can be very accurately estimated when the obstacle geometric shape is relatively simple*

#### **4.1.1 Schiphol Airport Case Study :**

In advance of commissioning TNO to conduct a Detailed Engineering Assessment (DEA) of the proposed development to predict the level of impact on radar performance by the proposed development TNO were requested to show how they validated their model.

TNO previously conducted a DEA for a wind farm development which was 8km from Schiphol Airport in the Netherlands. This has been detailed as shown in Appendix F. Schiphol is a very busy International Airport with both a Primary Surveillance Radar (PSR) and two Monopulse Secondary Surveillance Radars (MSSR). The Radars at Schiphol are of similar manufacture to those at Shannon Airport and Woodcock Hill. The empirical effect of the wind farm on the existing radars was identified. TNO had the appropriate clearance to use confidential data and a mitigation option was identified and implemented. In this case, the mitigation involved the provision of a new additional MSSR which provided coverage of any area potentially Impacted with integration into the Eurocontrol ARTAS

system thereby ensuring full Radar tracking of all aircraft to the satisfaction of the ANSP. The empirical analysis of impacts was critical to identifying the extent of any impact and the appropriate mitigation solution as implemented by the Dutch ANSP.

## 4.2 Detailed Engineering Assessment (DEA) – Wind Turbines at Knockshanvo

Following the provision of the Schiphol Airport case study, the Applicant instructed Ai Bridges to engage TNO to conduct a Detailed Engineering Assessment ( which is shown in Appendix G ) of the proposed development and to consider the existing baseline which includes the already consented wind farms in East Clare (Carrowmagowan, Lackereagh and Fahy-beg).

TNO follow the Eurocontrol Guidelines on how to assess the potential impact of wind turbines on performance of radar systems. For secondary radars all turbines within a distance of 16km and in Line of Sight need to be assessed. All of the wind turbines of the proposed development are within the 16km and in line of sight of the Woodcock Hill MSSR radar. This assessment also includes a cumulative assessment of the Oatfield development which is currently in the planning process. Following consultation with TNO it was confirmed that the Ballycar windfarm development, also in the planning process, falls outside zone of cumulative impact and was thus not considered.

It is noted that all of the wind turbines in the consented Lackereagh and Fahybeg developments are inside 16km assessment zone of the Woodcock Hill MSSR as shown in Figure 11. Also 7 of the turbines of the consented Carrowmagowan development are within the 16km assessment zone.

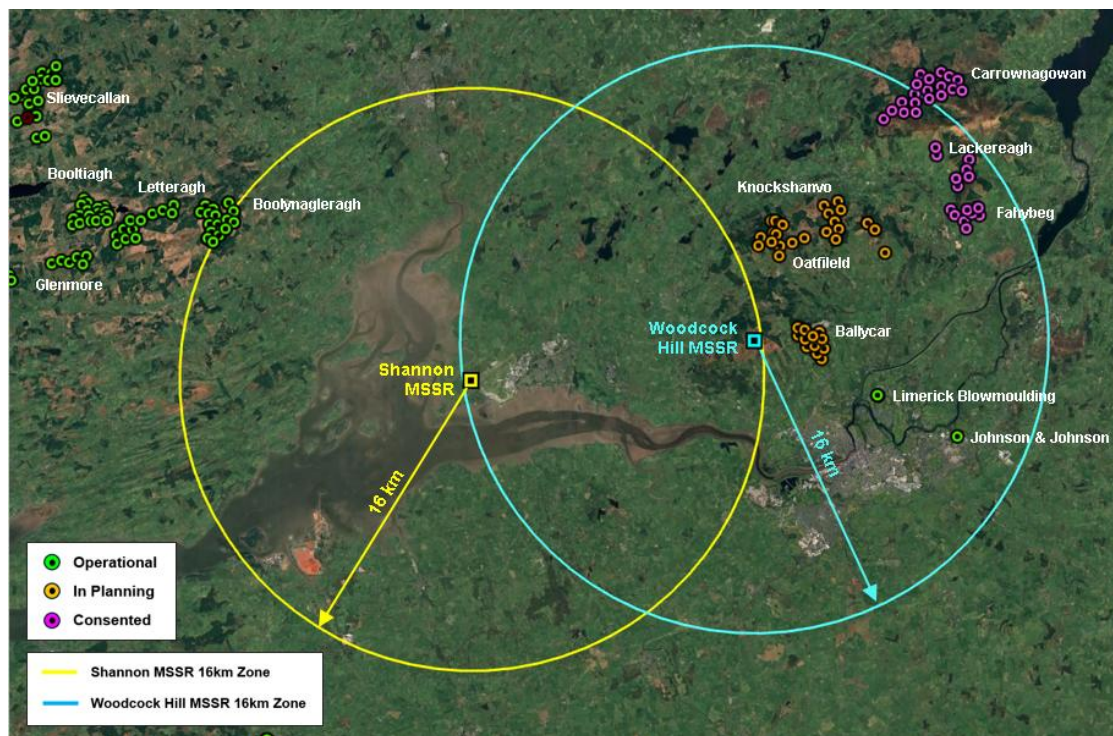
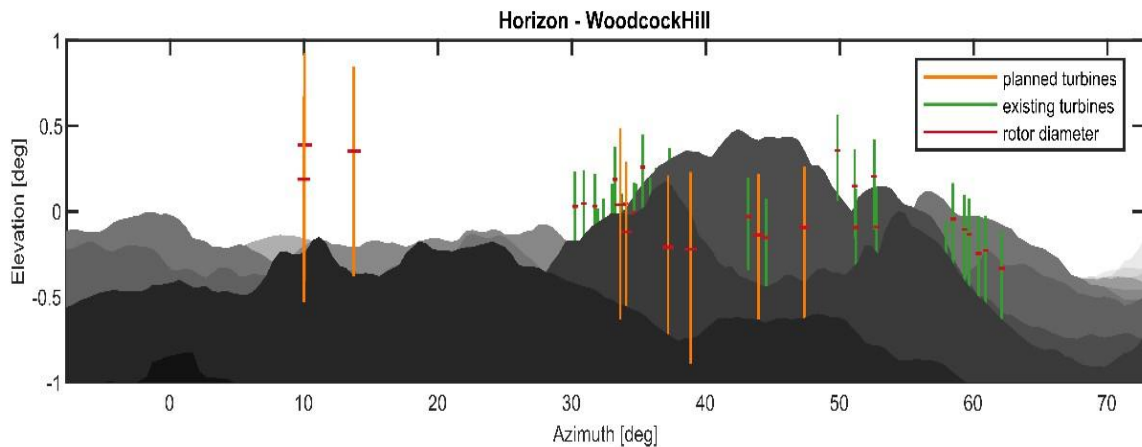


Figure 11 Operational, Consented windfarms and wind farms in the Planning Process that inside the Eurocontrol recommended MSSR 16km assessment zone for Shannon Airport MSSR. The consented wind farms in East Clare can also be seen, two of which are inside the Eurocontrol recommended MSSR 16km assessment zone for Woodcock Hill MSSR

This assessment report outlines the methodology by which TNO validates their model in Section 2. In Section 3, TNO include the specific wind turbine details that are assessed which includes the wind

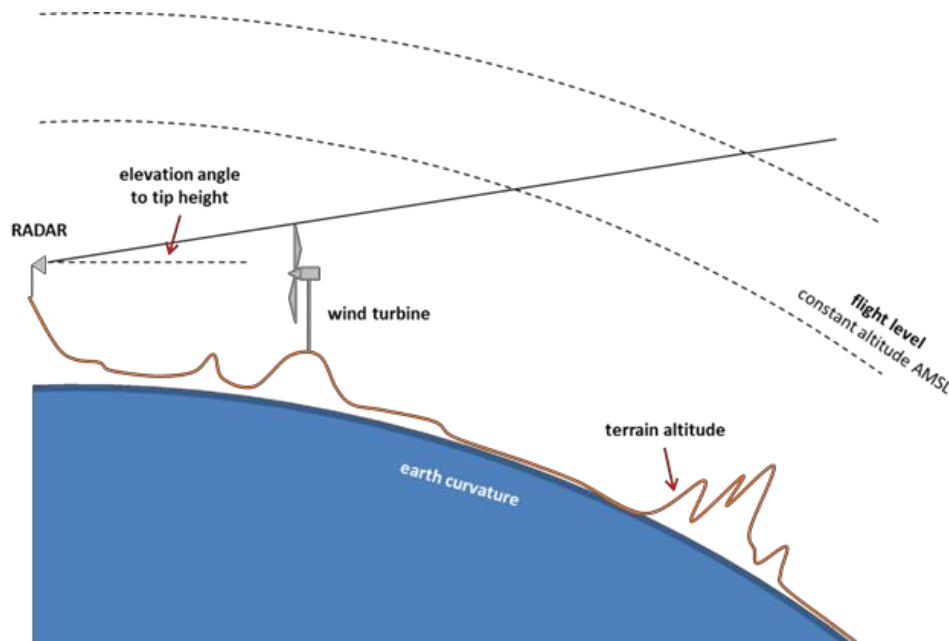
turbines of the proposed development as well as the consented wind turbines (Carrownagowan, Lackereagh and Fahy-beg ). The details of the Woodcock Hill Radar are also included. In Section 4 of the report, TNO then assess the effect of the proposed Knockshanvo wind turbines and the consented wind turbines and provides the results of a line of sight analysis. TNO have, for completeness, taken the already consented wind turbines as shown in Figure x below into account.

It is shown in Figure 12 below that all of the turbines can be “seen” ( in Line of Sight ) by the Woodcock Hill radar however there is a hill behind four out of the 9 proposed turbines. The Hill in the background limits the “view” of the radar so all aircraft targets behind this hill will not be seen by the radar and thus the hill has the greater impact of what the radar can see and not the 4 turbines. So the radar horizon is limited by the hill behind the proposed development.



**Figure 12 Line of Sights (to scale) Horizon of the already consented wind turbines (Carrownagowan, Lackereagh and Fahy-beg) as well as the wind turbines for the proposed development as seen from the MSSR.**

TNO explain the concept in relation to radar horizon in section 4.1. This is clearly explained by the aid of Figure 13 below. It is shown that the elevation angle from the radar to the turbine tip height of the wind turbine is indicated by a grey line. The MSSR radar replies of aircraft above this line are not influenced by the wind turbine. Aircraft replies below the line may be influenced by the wind turbine



**Figure 13 Overview of the overall Line of Sight showing the elevation angle to the turbine tip height**

TNO go on to provide an interpretation of what the Line of Sight towards one of the proposed , in this case T6, as seen from the radar at Woodcock Hill. Some of the wind turbines for the proposed development are located in between the radar system and a hill that obscures the Line-of-Sight of an aircraft at certain altitudes, as shown in Figure 14 In these cases, of which the example of T6 is shown, the aircraft is either behind this hill (i.e., below the dotted line) or is in direct Line-of-Sight of the radar without potential interference of the planned wind turbine (i.e., above the dotted line). At a range of 100 km, at the azimuth angle towards the wind turbine, a target below approximately 5581 feet the radar signal will be behind the hills, and above this altitude will not be affected by the wind turbine.

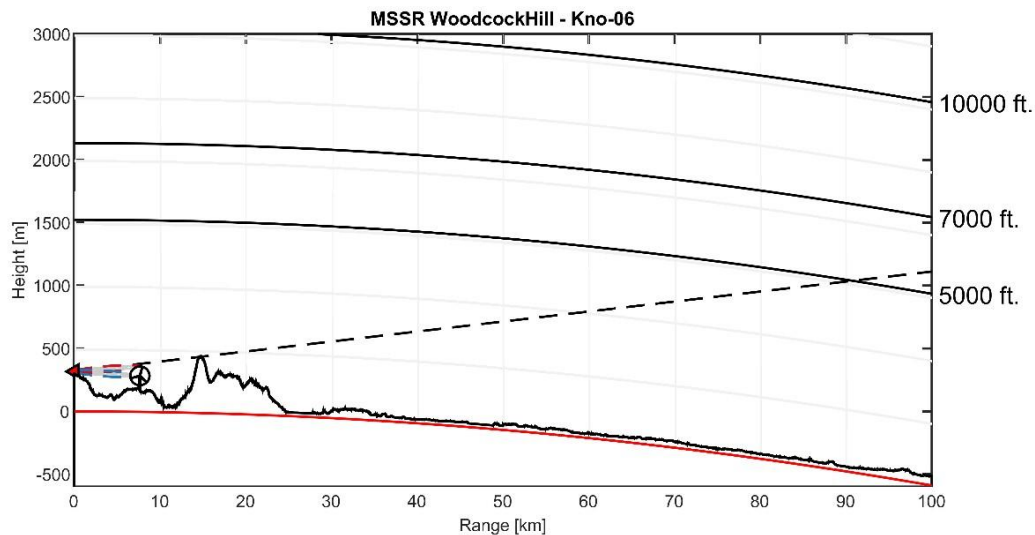


Figure 14 Overview of the overall Line of Sight showing the elevation angle to the turbine tip height

### Areas of Potential Impact :

The next step in the modelling process is to determine impact caused by the static part of the turbine (tower/hub) and the moving part of the turbine hub (blades). In Figure 15 below, the impact of the turbine hub is shown in the orange zone and the impacts of the turbine blades is shown in the red zone.

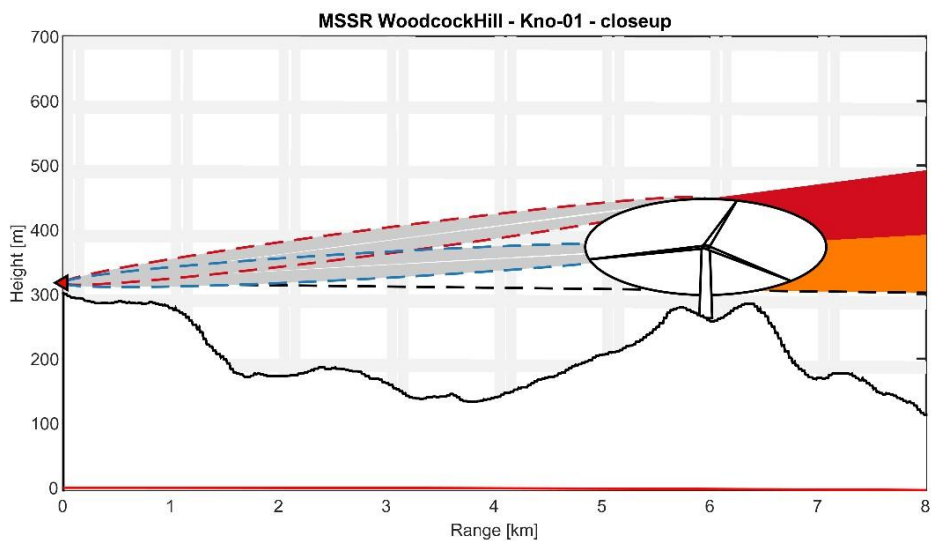


Figure 15 Line-of-Sight towards planned turbine T1 as seen from the Woodcock Hill MSSR.

In the red and orange areas the Woodcock Hill MSSR is not completely 'blind'. The red and orange colours indicate where impact of the wind turbines on the radar performance can potentially occur. In these regions the signal from an aircraft transponder towards the Woodcock Hill MSSR antenna passes one of the proposed wind turbines. This means that the wave front of the signal transmitted by the aircraft transponder will be disturbed by the wind turbine and does not necessarily mean that the impact on the position estimation of the aircraft target by the MSSR is significant. The error of the signal in the position estimation of the aircraft target due to wind turbines placed in the signal is then investigated.

### **Line of Sight Coverage :**

The results from the previous steps give an insight into the extent to which the proposed development can potentially affect the bearing estimate of the aircraft targets that are provided by the Woodcock Hill MSSR. This can be seen in Figures 16-18 below.

For each aircraft target height three scenarios are considered.

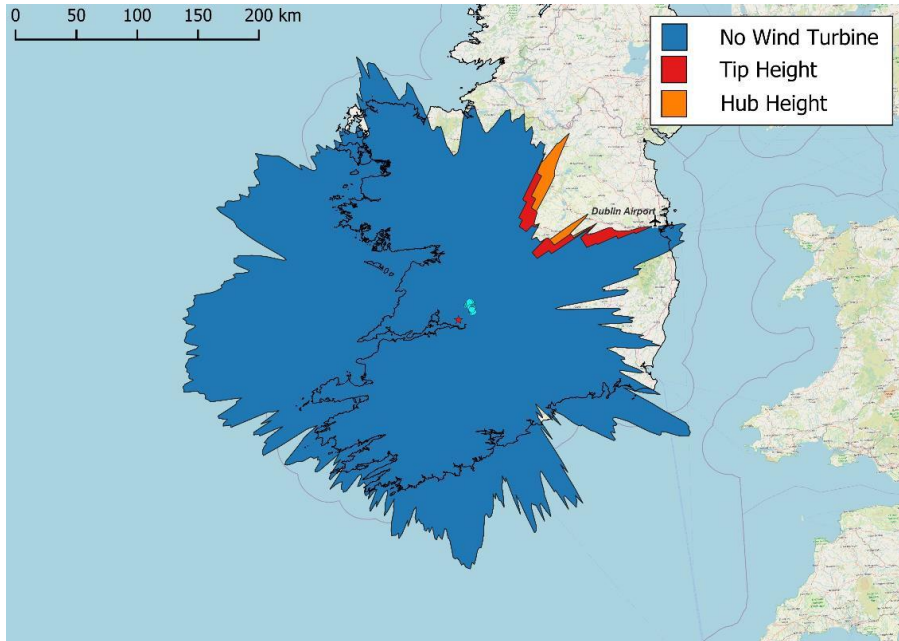
1. The coverage when already consented (Carrownagowan, Fahybeg and Lackereagh) turbines are considered
2. The coverage when the proposed development and already consented (Carrownagowan, Fahybeg and Lackereagh) turbines are considered
3. The coverage when the proposed development, the already consented (Carrownagowan, Fahybeg and Lackereagh) and Oatfield turbines are considered

By comparing these figures the effects of the proposed development on the Line-of-Sight coverage can be determined.

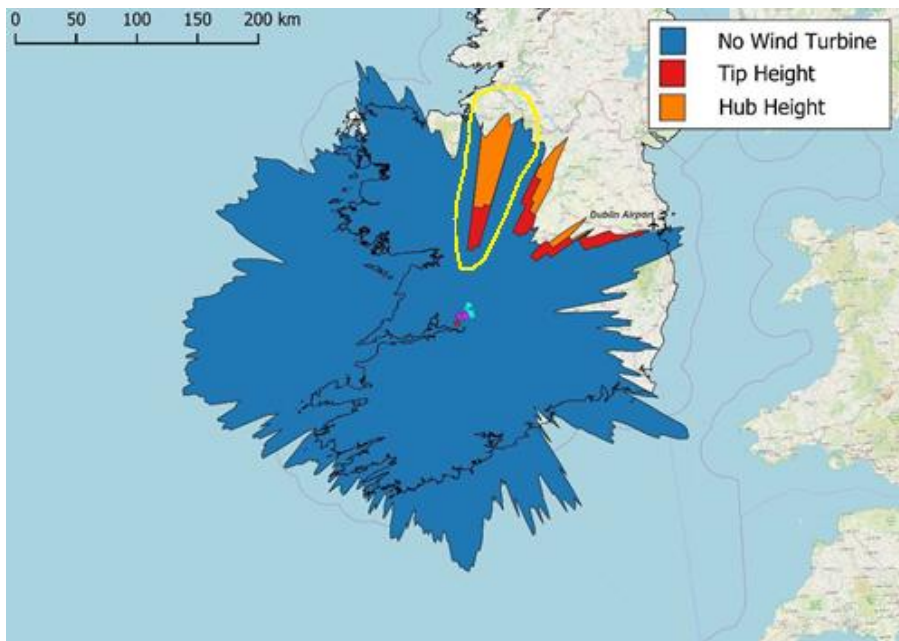
The Line-of-Sight coverage diagrams for the MSSR at target heights of 5000 feet has been shown below. The target heights 7000, 10000 and 35000 feet are provided within the assessment report (as shown in Appendix G, sections 4.15 to 4.23). The areas affected by the turbine hub height of the wind turbines are shown in orange. The areas affected from hub height up to the turbine tip height are shown in red. The Woodcock MSSR radar is indicated by a red star, the blue dots are the consented wind turbines, the purple dots are the proposed development turbines and the yellow dots are the Oatfield turbines.

The Line of sight coverage diagrams in Figure 16 - 18 below shows the areas of potential impact of the already consented turbines for the Carrownagowan, Lackereagh and Fahy-beg developments. The potential for impacts is shown at an azimuth sector between approximately 6° and 17° as seen from the Woodcock Hill which is over airspace in the general area of Longford and Cavan and over parts Offaly and Kildare. There are no orange or red impact areas over Dublin Airspace affecting flights coming from the east for aircraft targets at heights at 5000 feet.

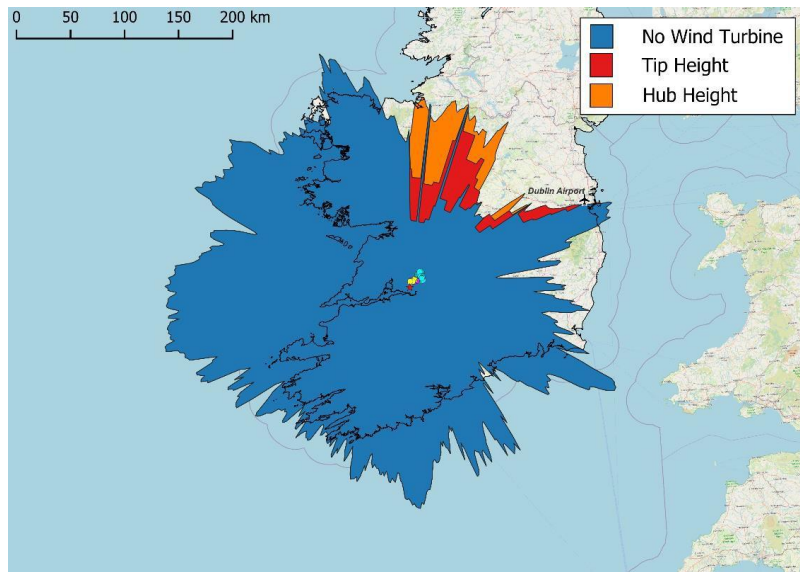
However It should be noted that for the service coverage diagrams at 7,000 feet and 10.000 feet there appears to be red zones shows the area of potential impact over Dublin Airspace due to the already consented turbines for the Carrownagowan, Lackereagh and Fahy-beg developments however there may be no degradation.



**Figure 16** Line-of-Sight coverage diagram for a target at 5000 ft AMSL as seen from the Woodcock Hill MSSR when the already consented (Carrownagowan, Lackereagh and Fahybeg) turbines are considered.

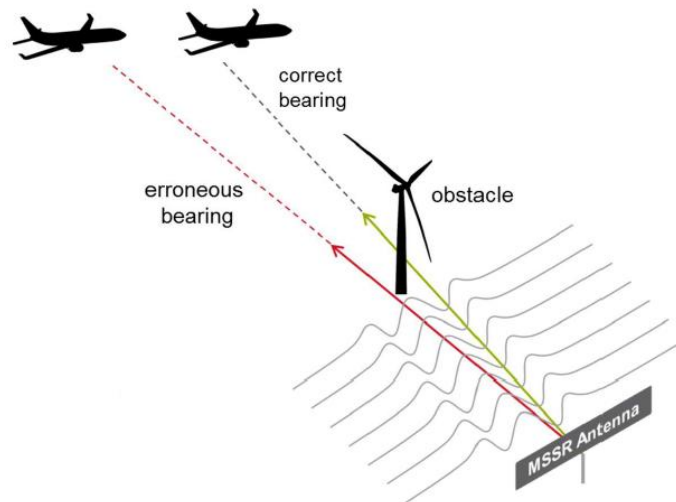


**Figure 17** Line-of-Sight coverage diagram for a target at 5000 ft AMSL as seen from the MSSR. All consented wind turbines, and the proposed development are considered



**Figure 18** Line-of-Sight coverage diagram for a target at 5000 ft AMSL as seen from the MSSR. All consented wind turbines, the proposed development and Oatfield development are considered

TNO in their assessment report provide an interpretation of the results and elaborate on the Off Bore-Sight (OBE) errors. TNO model shows that the presence of wind turbines as an obstacle between the MSSR radar and the target can cause an error in the estimation of the bearing to the target as shown in Figure 19 below. The extent of the bearing error is calculated by the validated TNO model. TNO present the OBE calculations for the Woodcock MSSR radar. The OBE calculations are valid for all flight levels in the line of sight analysis plots.



**Figure 19** Wind turbines positioned between aircraft targets and a MSSR radar can disturb the aircraft transponder signal introducing an estimate error in the bearing estimate. The angular difference between the aircraft's actual position and its position indicated by the radar is known as the Off-boresight error (OBE)

The consented planned wind turbines that have been included in the simulations, have an effect on the MSSR in an azimuth sector of 39°, from 26° to 65°. When the newly planned wind turbines at Knockshanvo are added, an additional region with an azimuth sector of 11°, from 6° to 17°, that has an effect on the MSSR is present. Subsequently, the additional wind turbines at Oatfield will lead to a further increase of this azimuth sector between -3° and 30°.

The secondary radar has Line-of-Sight to all wind turbines (see Sections 4.1 and 4.2). The regions where the turbines have an effect on the radar are dependent on the target height and are displayed in Section 4.3. From this, it can be observed that all three situations, with and without the newly planned wind turbines (at only Knockshanvo, and at both Knockshanvo and Oatfield), there could be an effect on the MSSR performance due to the newly planned wind turbines when the target is at a certain area.

The maximum absolute OBE that could occur due to the newly planned turbines at Knockshanvo differ based on the target height. At lower target height, the so-called orange area, where the boresight measurement is interfered by the mast and nacelle, the maximum absolute off-boresight error is found to be  $0.53^\circ$ . At higher target heights, the so-called red area, where the boresight measurement is interfered by only the blade standing in the upright position, the absolute off-boresight error equals  $0.62^\circ$ . The  $1\sigma$  standard deviation value measures  $0.143^\circ$  for the orange area and  $0.126^\circ$  for the red area.

In the situation where the newly planned wind turbines at Oatfield are added as well to the assessment, these errors are slightly different. In this case, the maximum off-boresight error is found to be  $0.48^\circ$  and  $0.59^\circ$  in the so-called orange area and red area, respectively. Also, the  $1\sigma$  standard deviation value is measured at  $0.157^\circ$  for the orange area and  $0.138^\circ$  for the red area.

In their conclusion TNO show that another existing MSSR (i.e. MSSR Tooman) can provide overlapping coverage in the sectors affected by the already consented and proposed development ensuring duplicated MSSR coverage, which is a requirement of the Eurocontrol Standard<sup>[17]</sup>, and maintaining surveillance performance where the Woodcock Hill MSSR shows reduced performance.

### **4.3 Boolynagleragh Wind Farm – Shannon Secondary Radar Combined with Boolynagleragh**

The Applicant has also commissioned Ai Bridges to engage with TNO to conduct additional Detailed Engineering Assessments to model and predict the impacts existing operational wind farms in the State and inside the EuroControl 16km Assessment Zone for MSSR Radar.

One of these operational wind farms is at Boolynagleragh. The results in the previous sections give insight to which extent the wind farm can potentially affect the bearing estimate provided by the MSSR. In this section we show the locations of the affected areas in the Line-of-Sight coverage diagrams or service coverage maps. Coverage diagrams are shown for targets at altitudes of 5000, 7000, 10000 and 35000 ft. A coverage diagram in Figure 16 above shows whether the performance of the Shannon Airport secondary radar can be influenced by the target at a given altitude. The TNO assessment ( as shown in Appendix H ) shows that the operational wind farm at Boolynagleragh has the potential to impact the Shannon Airport MSSR.

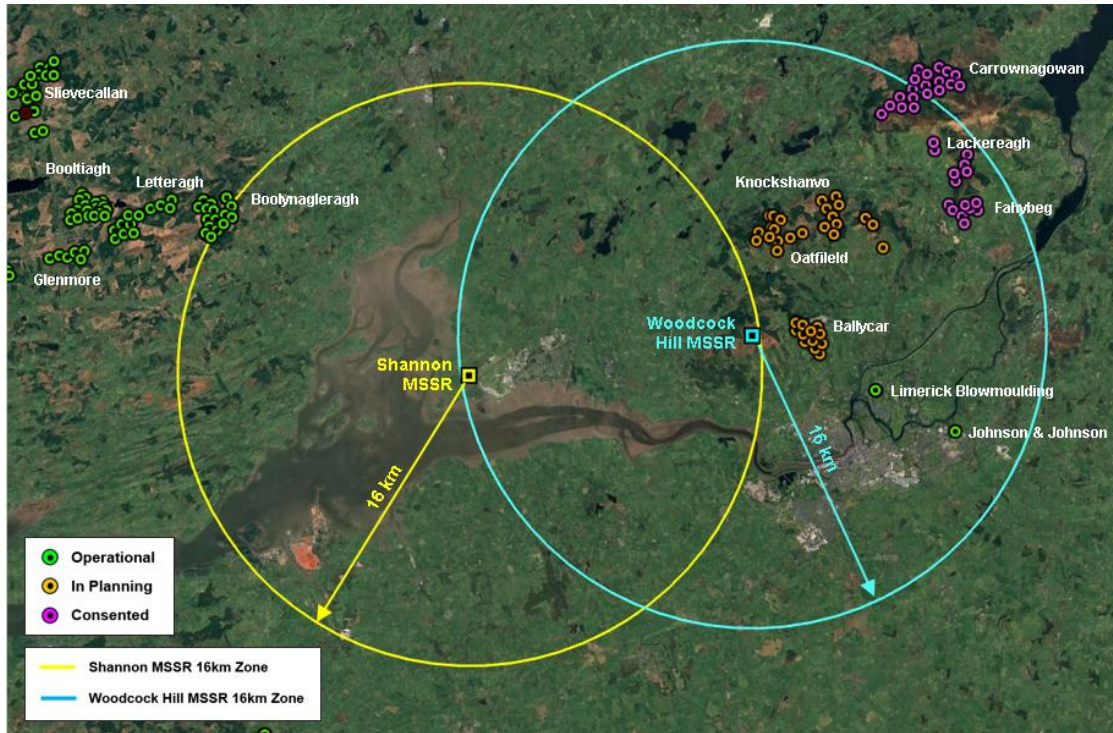
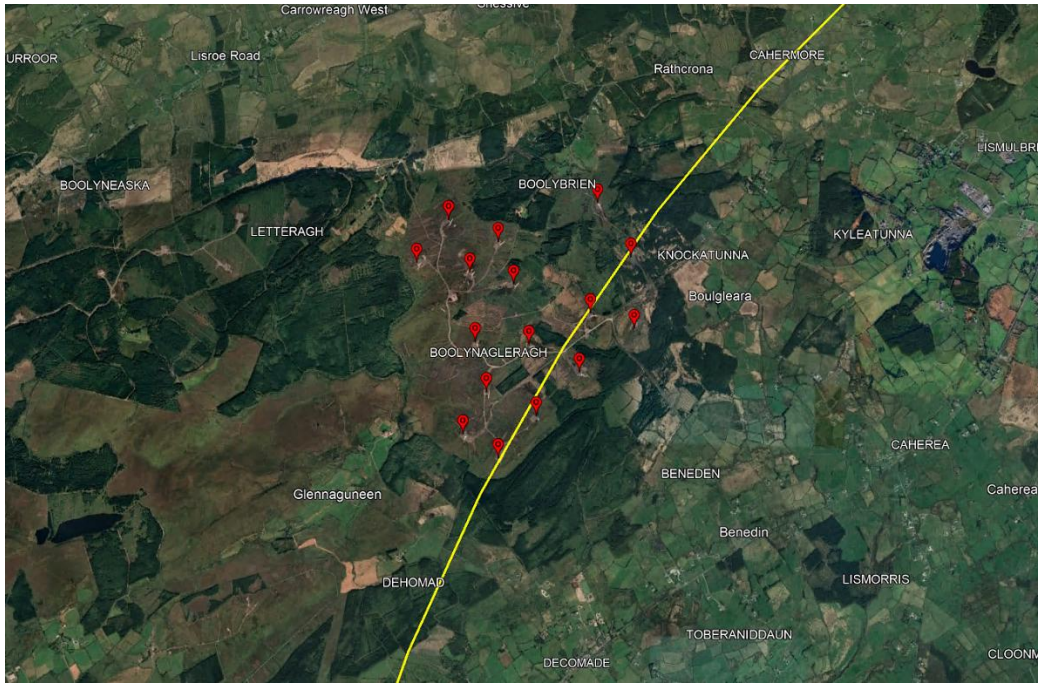


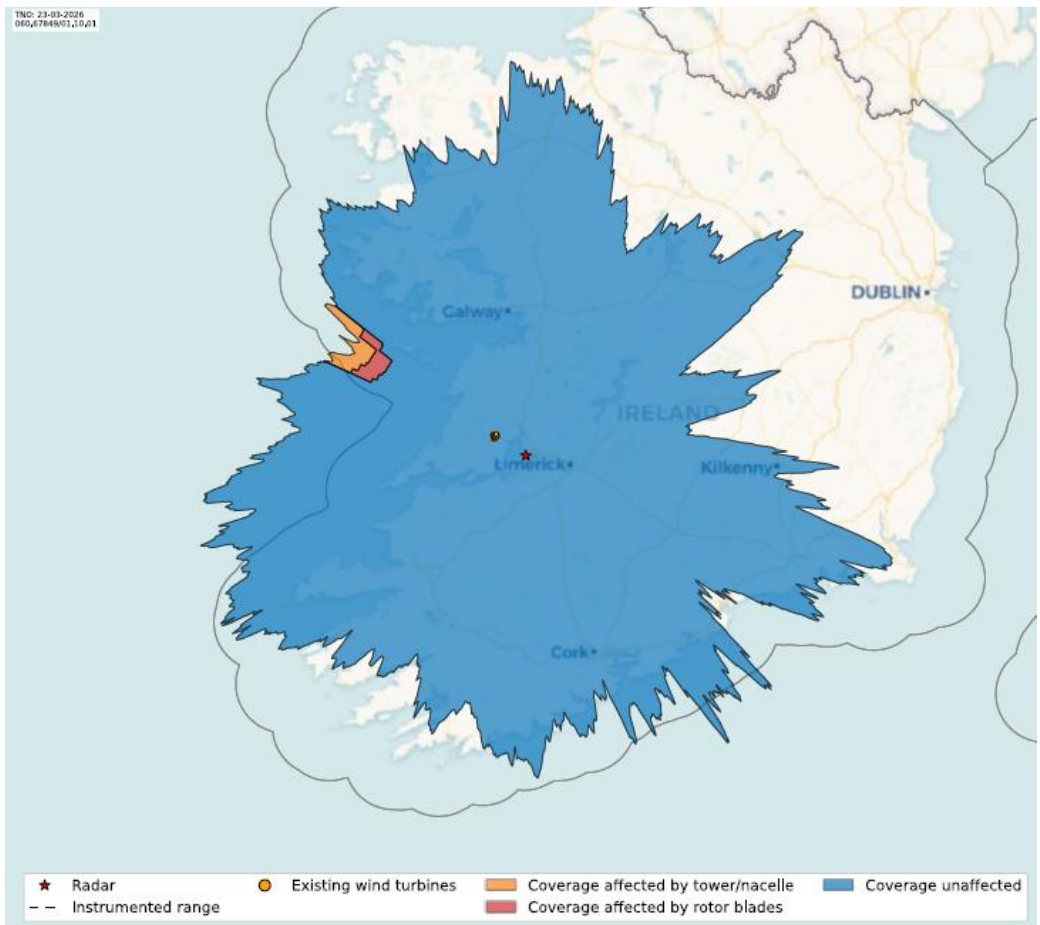
Figure 20 Operational, Consented windfarms and wind farms in the Planning Process that inside the Eurocontrol recommended MSSR 16km assessment zone for Shannon Airport MSSR. The consented wind farms in East Clare can also be seen, two of which are inside the Eurocontrol recommended MSSR 16km assessment zone for Woodcock Hill MSSR.



Figure 21 Boodynagleragh wind farm relative to the Eurocontrol recommended 16km assessment zone for the Shannon Airport MSSR as indicated by the yellow circle centred around the Shannon MSSR location.



**Figure 22 Boolynagleragh Wind Farm ( 16 turbines ) view showing five turbines are inside the 16km assessment zone as recommended for assessment under Eurocontrol.**



**Figure 23 Potential Impacts Area from the Boolynagleragh Wind Farm on Shannon MSSR**

## 4.4 Australian Case Study – Australia MSSR Radar Assessment

TNO were commissioned by an Australian Wind Farm developer to conduct a detailed engineering assessment of the potential effects of a 70-turbine wind farm development on the MSSR performance of radars operated by the Australian ANSP, Airservices Australia (ASA).

The wind farm development was located 10km from the nearest turbine and 15km from the farthest wind turbine from the en-route MSSR ( Indra manufacture ) at Mount Bobbara . The wind farm is also to the north-east of another combined approach PSR ( STAR 2000 ) and MSSR located at Mount Majura which is near to the Canberra International Airport and both radar PSR\MSSR are from Thales.

The TNO simulation software tool , PERSEUS, was used to assess cumulative effect of the wind farm radar service coverage from both Mount Bobbara and Mount Majura in combination. ( Mount Majura is used for Approach for Canberra International Airport). Both radar sites were found to be influenced by the proposed development .

Obstacles such as buildings, telecoms masts and wind turbines are known to cause deflection errors on MSSR radar performance. The MSSR radar interrogator sends request to the transponder in the target aircraft. The transponder sends a reply and which is received by the MSSR antenna. The angle of arrival at which the transponder reply is determined by the delay difference across the elements of the antenna. When obstacles ( buildings, telecoms masts, with turbines etc. ) are within the line of sight of a MSSR radar, they may interfere with the signal to the target aircraft resulting in what is known as Off Boresight Errors (OBE), see graphical illustration below in figure 24. The obstacle can cause the radar signal to be deflected resulting in an error of the signal bearing.

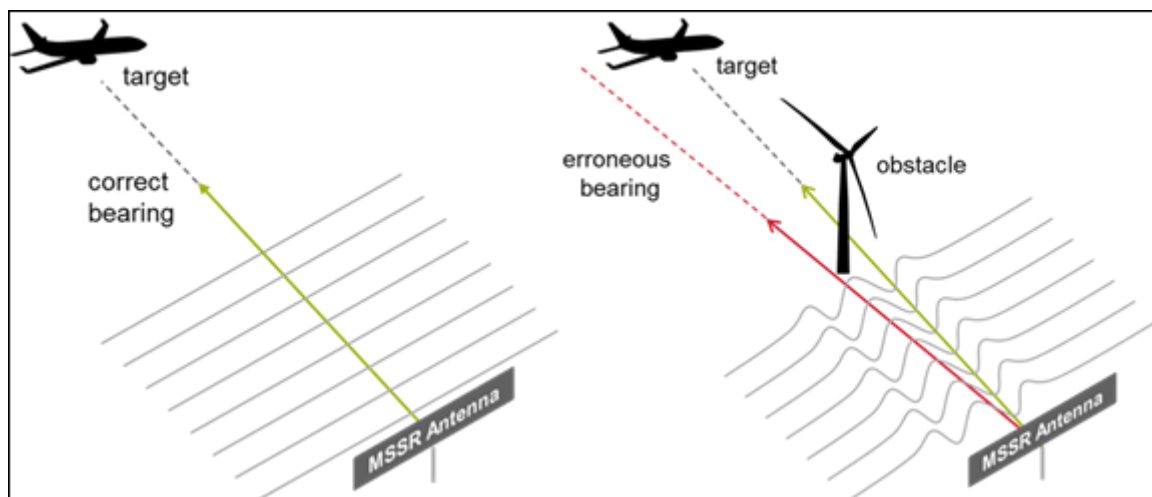


Figure 24: Off Boresight Errors due to a wind turbine

TNO performed Line of Sight analysis from the MSSR radars to the wind turbines and these calculations were performed at aircraft target heights of 3000ft, 5000ft, 10000ft and 20000ft. The calculated Off Boresight Error is valid at all flight levels as shown in the Line of Sight Coverage diagrams in Figure 13 to Figure 20 (as shown in Appendix D). While the Line of Sight calculations provided an overview of the azimuth angle in which the performance of the MSSR at both Mount Bobbara and Mount Majura may be impacted by the wind farm development, the actual azimuth angle

error of wind turbine interference was calculated using the TNO software tool. All calculations were performed for different positions of the aircraft and at different angle of orientation of the MSSR antenna to allow a statistical distribution spread to allow a determination of the positioning errors. The position error depends on the classification of airspace. In certain areas of operational airspace, which is the responsibility of the ANSSP, the accuracy for the aircraft position will be different and necessary to ensure that the correct separation between aircraft is maintained for both terminal approach and en-route airspace.

The TNO software simulation is able to show that as the distance from the radar to the target aircraft increases so does the bearing error and this error can then be converted into a cross-range error in meters for various distances from the MSSR, details of which are included in Appendix D, section 5.6. TNO provide a graph showing plot of error versus tracking error in Figure x below. It can be seen that the predicted plot error against the actual tracking error of the radar system assists in validating the accuracy of a model. (as shown in Appendix D, section 6).

The plot errors were calculated and graphed against the track error. TNO makes reference to how the an ATC tracker processes the radar plot of a target aircraft and how in some cases that can use a filter to attenuate errors in the plots and how next position predictions can be performed and how track update of the target is a weighted average between the predicted position and the plot position. The TNO calculations allow the plot position to be mapped against the track position. In the case of the 70-turbine wind farm Airservices Australia requested that the inherent MSSR system errors be calculated and assessed as well. The data for this assessment was provided by the ANSP the radar manufacturer, Indra, which in turn provided this data to TNO.

This data allowed TNO to accurately calculate the position error, which involved calculation of the random errors and the range bias errors ( i.e. inherent system errors of the radar and caused by system hardware issues etc. ). Based on the minimum range error requirements that were provided by the ANSP ( without turbines ) the acceptable range at which the position error exceeds the 95% confidence range is approximately 195NM. This range was then plotted around the Mount Bobbara MSSR which is the error contour required by the ANSP.

This allowed TNO to then combine the MSSR Line Of Sight Coverage at various altitudes with the error contour map. TNO provided the Line of Sight Coverage maps for the MSSR radars at Mt Madura, Mount Bobbara. The minimum accuracy requirements for the positioning error could not be met for the Mount Bobbara MSSR performance and also could not be met by the by Mount Madura MSSR. The zone where the position error did not meet the minimum accuracy requirements of the ANSP when considering the Line of Sight coverage the Error Contour for Mount Bobbara on its own, is shown in Figure 28 to Figure 30,

The TNO Assessment was also used to investigate the potential mitigation measures that were available to the ANSP. The assessment allowed the ANSP to look at the alternative option of combining or fusing the track and plot data from Mount Bobbara, Mount Madura and the existing en-route Mount Macedon MSSR. The TNO assessment was able to show that at target altitudes of 8000ft and 10000ft the Mount Macedon does not provide coverage over the area where the Off Boresight Error effects are caused by the wind farm . However it was confirmed that Mount Macedon provides full coverage could take over at higher radar vectoring altitudes of 20,000ft and above. In this case the TNO detailed engineering assessment was able to inform the ANSP and provide the assurances required that the deflection errors caused by 70-turbine wind farm would not have an impact on en-route traffic above 20000ft. It was shown that Mount Macedon was able to provide radar coverage over the area where the combined Mount Bobbara and Mount Majura fused radar coverage were unable to compensate for the Off Boresight Errors caused by the wind farm development.

TNO used their software simulation tool to predict the Off Boresight Errors caused by the 70-turbine wind farm on the MSSR performance. The TNO modelling tool accurately identified the issues of interference and assisted the ANSP to model the worst-case scenario effects which evidenced the accuracy of the model by showing the correlation between the predicted position error plot against the track error. This was achievable based on the data that was provided to TNO from the radar

manufacturer. The simulation provided the ANSP with sufficient assurance that a neighbouring MSSR radar at Mount Macedon would provide the required coverage for En-Route surveillance.

TNO also highlight, in their conclusions, reference to other forms of mitigation which are available but that this is the responsibility of the ANSP in question to decide what the most suitable form of mitigation is operationally acceptable.

## 4.5 Woodcock Hill MSSR – Radar Signal Deflections Modelling

The key issue of Radar Signal Deflections that has been highlighted by AirNav relates to the impacts caused by a telecoms mast on radar signals from the Woodcock Hill. AirNav completed a report on this issue in July 2025 following a meeting with Wind Energy Ireland (WEI). This report was distributed to WEI members and the Applicant reviewed same.

At a meeting on 01 October 2025 AirNav requested that the Applicant provide examples and case studies of where wind farms can co-exist with radar sensors and that these sensors could continue to operate as safe as they were before the construction of the wind farm. AirNav advised that they would accept any application of radar sensor technology, either primary (PSR) or secondary (SSR), and any manufacture of radar sensor. AirNav requested that any example be the same distance as Knockshanvo is to Woodcock Hill.

In order to provide these examples the Applicant instructed Ai Bridges to engage TNO conduct Detailed Engineering Assessments to address the most important issue that can arise whenever a wind farm is near a secondary radar system i.e the issue bearing errors.

SSRs differ from PSRs in a number of ways. PSRs do not depend on cooperation of aircraft, they merely measure range, bearing and sometimes also elevation angle and radial velocity. SSRs demand that aircraft cooperate, i.e., the aircraft actively participates in its detection. The SSR sends out an interrogation signal at 1030 MHz. The target, carrying a radar transponder, subsequently replies by transmitting a response signal at 1090 MHz. This response contains additional information regarding the target, e.g., barometric altitude (mode C) and an identity code (mode A). In the case of monopulse SSR (MSSR), the system is capable of making a precise bearing estimate of the target from a single reply signal (hence, monopulse). The bearing estimate is generally accurate within a fraction of a degree ( $\sim 0.05^\circ$ ). The presence however of an obstacle (like a mountain, building or wind turbine) between the MSSR antenna and the target can cause an error in the estimation of the bearing to the target

The Detailed Engineering Assessment for the proposed development along with the assessment of the operational Boolynagleragh windfarm has been conducted based on a validated assessment methodology. These assessments have been carried out based on Eurocontrol Guidelines. TNO have modelled all planned and consented wind farm developments to identify the areas where the angle measurement of the Woodcock Hill MSSR may be influenced within the 16km assessment zone of the Woodcock Hill MSSR

The applicant proposes that the validated simulation model that has been used to accurately identify the potential impacts from the proposed development on the Woodcock Hill MSSR and in part provide measurable evidence to progress discussions around the optimal mitigation solutions that have been proposed.

If a wind turbine is positioned between the target and the radar, the received electric field is distorted both in phase and in amplitude. This is illustrated in Figure 25. The distorted field effectively changes the weight factor at each antenna element, thus, changing the shape of the sum beam and difference beam. As the two beams are influenced differently by the wind turbine, so is the signal strength

measured in both beams. Therefore, when the signal strength is compared to estimate the bearing, an error is introduced.

To estimate the bearing error TNO used solution for an incident plane wave on a cylinder with fixed radius and infinite length. The method calculates the phase and amplitude of the perturbed wave front on each antenna element. From this the bearing error is determined. The method is described in full in [2]. In this reference the method has been validated using real data of an MSSR partially obstructed by a metal mast of width ~2 meter at a range of approximately 600 meter.



**Figure 25 The telecoms masts at Woodcock Hill one of which was identified by AirNav causing deflections of the radar beams from the Woodcock Hill MSSR ( photo taken with back to the MSSR )**

The Applicant is willing to collaborate with AirNav and is prepared to model the reported deflection impacts from the telecoms masts at Woodcock Hill MSSR and compare this with the actual on recorded data from the MSSR.

This modelling methodology can be used by AirNav for their own review has shown deviations positional accuracy when the SSR are shadowed by neighbouring man-made structures (such as communication masts, buildings and wind turbines).

Modern SSR monopulse receivers estimate the azimuth bearing of aircraft through the orientation of the incident planar wavefront. The telecoms mast obstacles in the radar beam propagation path diffract part of the electromagnetic wave energy and as a result, the electric field across the antenna array is subject to a disturbance ( as shown in the TNO Report, Appendix 3 – section 2.1 )

The resultant azimuth error in the shadowed sector depends on the width and height of the obstacle and on its position relative both to the radar and the target aircraft. A method to estimate the azimuth error curve due to obstacle shadowing based on cylindrical diffraction theory has been used . A comparison between measured data and the estimated error curves reveals that azimuth errors can be very precisely calculated.

Accurate estimation of azimuth errors due to obstructions has increasing significance for operators of SSRs. Radar performance must continue to be safeguarded in the face of increasing pressure to allow development on or near radar sites.

The validated assessment, as completed by the Applicant, that identifies the areas of potential impacts caused consented, planned and operational developments provides a valid method wind turbine impact assessment.

## 5. Response Summary :

### **Instrument Flight Procedures :**

It is the Applicants understanding from consultations that took place in October 2025 that AirNav is currently undertaking a re-design of the IFP's which was scheduled for September 2025 but that has been put back to Q2/Q3 2027.

The Applicant also understands that that the implementation of the State PBN plan will reduce the impact to IFP's and the potential for the proposed development at act as obstacles have been programmed.

The Applicant also understands that AirNav they are carrying out a cumulative impact assessment with FCSL on the potential impacts of the wind farms in East Clare, and the minimum sector altitudes required to manage flights descending into Shannon, which can be achieved at the higher altitude of 2400ft.

### **Radar Surveillance Systems at Woodcock Hill Facility :**

It is the Applicants understanding from consultations that took place on 01 October 2025 that the undertaking of a re-design of the IFP's which was scheduled for September 2025 has been put back to Q2/Q3 2027.

The Applicant commits to working with Air Nav Ireland, Shannon Airport Authority to clearly identify the impacts which are likely to occur through modelling in an empirical manner and to identify an optimum mitigation solution should this be required.

The Applicant has recently engaged with TNO, who has modelled and predicted empirically the level of impacts of an extension of 4 turbines to an existing wind farm at the West Port area of Amsterdam, approximately 8km north of International Airport at Schiphol. The Dutch Civil Air Control (LVNL) were concerned about the impact these wind turbines would have on their primary and secondary radars. TNO, who take a formal role in the Netherlands, assisted

TNO also carried out a Detailed Engineering Assessment for a 70-turbine wind farm Australia to assess the potential impacts the International Airport at Canberra with both a Primary Surveillance RADAR (PSR) and two Monopulse Secondary Surveillance Radars (MSSR). In this case the TNO detailed engineering assessment was able to inform the ANSP and provide the assurances required that the deflection errors caused by 70-turbine wind farm would not have an impact on en-route traffic above 20000ft. It was shown that Mount Macedon was able to provide radar coverage over the area where the combined Mount Bobbara and Mount Majura fused radar coverage were unable to compensate for the Off Boresight Errors caused by the wind farm development.

TNO have provided the details of their model validation strategy in Section 4.1. The Applicant believes that the examples and case studies provided demonstrates that the methodology to predict radar system performance are based on credible simulation models.

### **Mitigation Options – Instrument Flight Procedures :**

The applicant is accepting of the need for financial support the funding of additional resources that may be required by AirNav to conduct further flight procedure designs and radar upgrades as part of their PBN rationalisation plan and scheduled Radar Facility upgrades in the coming years. The applicant also accepts that the expectations ofc AirNav and Shannon Airport Authority's expectations in relation to safe operations, would need to be met i.e. any mitigation measure solution would be safe and ensure an efficient air traffic flow.

The applicant would be willing to contribute its share of the costs associated with any implementable and viable mitigation measure solution, as required, on a pro-rata basis with any of the listed projects that are granted a planning consent. During the engagements with the AirNav in 2022 they stated

*“ Aside for the costs in production of further assessments as referenced, system upgrades for filtering, flight procedures changes, ATC changes to support the mitigate for the new obstacles, as well as continuing additional costs associated with more flight check activity on an bi-annual basis, has the potential to cost the ANSP in the region of €200,000.00+, should planning be granted as proposed. “*

### **Mitigation Options – Radar Surveillance Sensors :**

The Applicant believes that it has provided relevant evidence and case studies that proves that the final remaining issue of deflections can be modelled and also to inform further collaboration with AirNav discussion on mitigation options

### **Conclusions :**

The Applicant acknowledges the notice to conditions set out by AirNav and the Shannon Airport with respect to the outstanding aviation safeguarding issues in relation to the proposed development and is fully committed to resolving these in order for the proposed development to proceed

The applicant would welcome the opportunity to engage with AirNav Ireland and Shannon Airport to discuss mitigation solutions that have been presented in the Instrument Flight Procedures Safeguarding Assessment, the Radar Mitigations Options Report and the evidence and case studies that has been requested by AirNav in 2025 following meetings and further consultation.

The Applicant is accepting of the need for financial support and the funding of additional resources that may be required by AirNav as part of its re-design of IFP's for Shannon Airport scheduled in Q2 or Q3 2027. The Applicant understands that this re-design of the IFP's currently in use at Shannon Airport coupled with the implementation of the State PBN Plan scheduled for completion by 06 June 2030 will reduce the impacts of the proposed development to the IFP's which the Applicant understands

The applicant is accepting of the need for financial support and the funding of additional resources that may be required by AirNav as part of the scheduled Radar Facility upgrades in the coming years. The Applicant also accepts that the expectations of the AirNav and Shannon ATC expectations in relation to safe operations, would need to be met i.e. any mitigation measure solution would be safe and ensure an efficient air traffic flow.

The applicant would be willing to contribute its share of the costs associated with any implementable and viable mitigation measure solution, as required, on a pro-rata basis with any of the listed projects that are granted a planning consent.

As such, the Applicant here confirms that should An Comisiun Pleanála deem it appropriate, a planning condition attached to any grant of planning permission issued requiring that turbines T01, T02 and T03 will not be constructed until the measures are in force, is acceptable. Suggested wording is set out below:

*Turbines T01, T02 and T03 as identified on the plans and particulars accompanying the planning application shall not be constructed until such time as the IFP re-design measures relating to Shannon Airport are in force.*

*Reason: in the interests of aviation safeguarding*

The Applicant, on foot of the recent information received from AirNav in January 2026 in relation to radar sensor parameters in operation in the State, believes that the Detailed Engineering Assessments and Case Study examples support the requirements by way of software modelling that accurately model the mitigations measure proposals and concepts contained within the updated Radar Mitigations Options Study prepared by Cyrrus in March 2026.

Mitigations are implementable prior to construction of the Knockshanvo project, by way of condition placed on the project that the operation of the project cannot commence until AirNav concerns are addressed.

The Applicant sought out the evidence, as requested by AirNav and seek to present this evidence as part of their response.

The Applicant has requested the radar data to assess the claim by AirNav that existing Telecoms Mast to allow modelling of the Woodcock Hill Radar Impacts in order to address the final remaining issue of “deflections”.

The Applicant still maintains its position that it is willing to contribute its pro-rata share of a financial contribution associated with any implementable and viable mitigation measure solution.

The Applicant believes that the mitigation options proposed by Cyrrus are credible and that they have provided the MSSR assessment and a simulation model that quantifies empirically the exact level of impact that may be caused by the proposed development on the Woodcock Hill MSSR.

The Applicant would also be amenable to An Coimisiún Pleanála inserting a planning condition that the Applicant agrees with AirNav Ireland, Shannon Airport Authority and the IAA in relation to the optimisation of Woodcock Hill MSSR to be undertaken and its financing prior to commencement.

The Applicant believes that they have provided evidence requested by AirNav as well as the precedents that there are consented and operational windfarms inside the 16km distance at which Eurocontrol recommend impact assessment. The Applicant believes the evidence provided can be used to assist the implementation of acceptable and practical mitigations.

## Appendix A - Knockshanvo Meeting Notes with AirNav

## MEETING MINUTES

Project	Knockshanvo	
Meeting Purpose	Meeting with AirNav	
Meeting Time/Date	11:30am 1 <sup>st</sup> October 2025	
Attendance	Name	Org.
Present	Sandra Kelly(FuturEnergy Ireland)	
	Paul Blount(FuturEnergy Ireland)	
	Sinead O Malley(FuturEnergy Ireland)	
	Juliet Ryan(FuturEnergy Ireland)	
	Kevin Hayes(Ai Bridges)	
	Catal MacCriostail(AirNav)	
	Charlie O Loughlin(AirNav)	

### Introduction & Project Overview

The meeting commenced with introductions from all attendees. Paul Blount kicked off the meeting with a brief summary of Knockshanvo, the project status and timelines as follows:

- The project is currently at the planning application stage.
- Even with immediate resolution of aviation issues, earliest possible construction completion is estimated for 2030–2031.
- Dependencies include grid connection, route market process, and planning permissions.

### Instrument Flight Procedures

- Redesign of the IFP's scheduled for release in September 2025 has been put back to Q2/Q3 2027,
- The implementation of the PBN plan will reduce the impact to flight procedures and the potential as the obstacles have been programmed.
- AirNav are in the process of carrying out a cumulative impact assessment with FCSL on the potential wind farm in East Clare, and the minimum altitude sector required to manage flights descending into Shannon. This can be achieved at the higher altitude of 2400ft.

## Radar Safeguarding

- CmC opened with context on the significance of Woodcock hill Radar and how it serves enroute phases of flights and manages significant traffic from the east. Any interference or false radar signals generated by wind turbines can impact operations during these flight phases
- Clarification on whether Knockshanvo was part of the Oatfield project was asked or to which project/turbines does this call relate to.
- SK showed a map with the Knockshanvo & Oatfield turbines and the number of turbines each project relates to.
- SK committed to issuing AirNav with a shapefile of the 9 Knockshanvo turbines.
- Concerns were raised by CoL about radar deflections and false signals caused by wind turbines, which can degrade radar accuracy and safety in controlled airspace, especially beyond 150-250 NM from radar sites. He highlights the lack of evidence supporting coexistence of large wind farms and radar operations without adverse effects. Aviation authorities are not permitted to degrade radar safety standards, and any mitigation must be proven not to compromise operational safety. This reflect the only remaining issue.
- Potential mitigation includes upgrading radar systems or installing additional radar sites to maintain coverage and safety. There are, however, the complexity, cost, and technical challenges of such upgrades, for radar equipment and infrastructure, with ongoing maintenance expenses. Alternative technologies like wide-area multilateration were considered but found suboptimal for the region's unique geography
- CoL expressed openness to reviewing evidence from developers or consultants demonstrating radar coexistence with wind turbines, at distances of 150NM – 250NM. Ideal evidence would include radar data screenshots showing no adverse deflections within safeguarding zones.

## Conclusion and Next Steps

The call concludes with plans:

1. To provide the correct data & turbine locations for the Knockshanvo project
2. to continue collaboration between AirNav and Futureenergy Ireland, aiming to resolve outstanding safety issues and provide clear evidence to support the project.
3. Further meetings once detailed analysis is carried out by Ai Bridges on behalf of Futureenergy Ireland and of which is provided to AirNav.

## Appendix B - AirNav Surveillance Description of Woodcock Hill Radar Deflections



## Surveillance description of woodcock Hill Radar signal deflections.

Report drafted by:

Charlie O'Loughlin Domain Manager Surveillance M&E systems

Date:

10th July 2025

### Executive Summary:

#### Background:

Woodcock hill Secondary radar in Co Clare provides radar position reports used by:

- Ballycasey Enroute Air Traffic Control Centre
  - AirNav provides 5 Nautical mile horizontal and 1000 feet vertical, aircraft separation in Irish En-route airspace. Aircraft transiting Irish En-route airspace are offered direct dynamic routing and are not restricted to rigid routes, resulting in reduced aircraft carbon emissions through fuel savings.
- Dublin Air Traffic Control Centre.
  - In Dublin AirNav provides 3Nm Horizontal and 1000 feet vertical aircraft separation.
- Dublin, Cork and Shannon ATC Tower services.

#### Woodcock Hill Radar Deflections:

Radar performance analysis of Woodcock Hill radar has highlighted that a communication mast 30m in height located at a 7 degrees azimuth and 730m distance from the Woodcock Hill Radar (see figure 1) impacts the measured positions of aircraft flying beyond 150km out 400km from the radar at the same bearing as the mast.

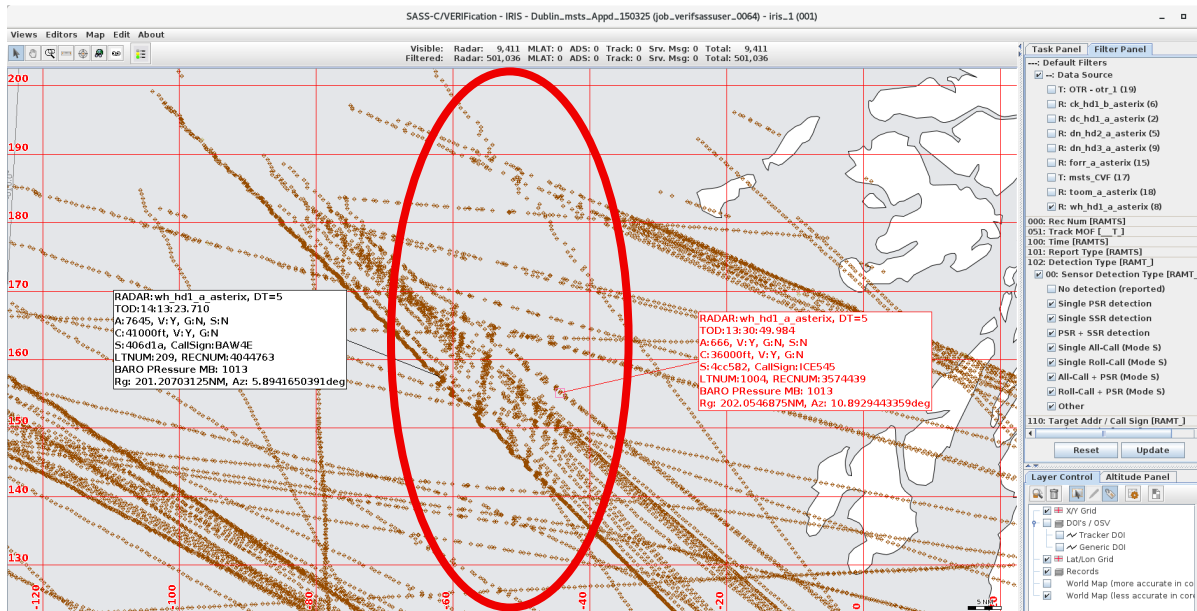


Figure 1: Woodcock hill Radar with red line to indicating the relative position of mast.

Deflections occur when a Radar interrogation signal is deflected by the metal in the mast which introduces an error in the measured bearing of the Aircraft. This bearing error increases with range of the aircraft from the radar, becoming significant at ranges beyond 200km. The radar bearing errors become an issue when the deflected Radar tracks are fused with the track data from other radars which calculate a different position for the aircraft track, and the deflected track is not associated with the true track position and a new Duplicate track is generated. This may result in dual aircraft tracks on the ATC screens which set of safety-net alarms such as Short-term conflict Alert (STCA) and Duplicate (DUPE) alerts. These alerts distract Air Traffic controllers who may attempt to deconflicting real Air traffic tracks from tracks that do not physically exist. Each Safety Net Alarm initiates a safety occurrence report.

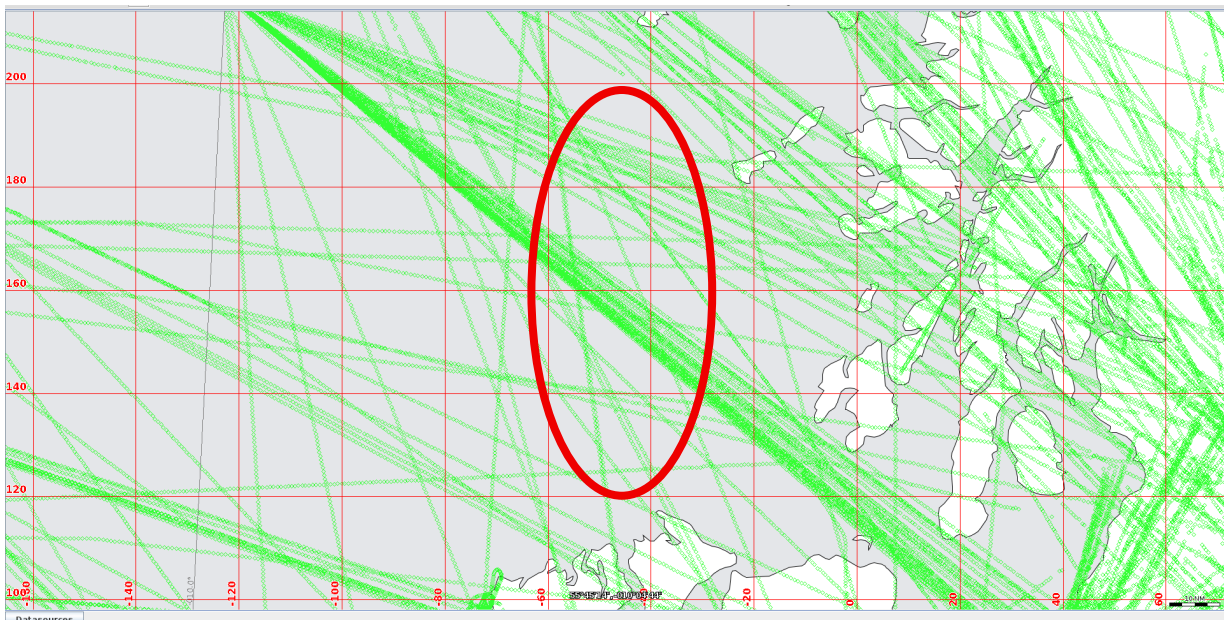
## Impact of 30m mast at 7degrees and 730m from Woodcock Hill

The following screen shots are samples of the radar analysis picture obtained using Eurocontrol analysis software of radar data recordings of the area >140Nm from Woodcock Hill radar.



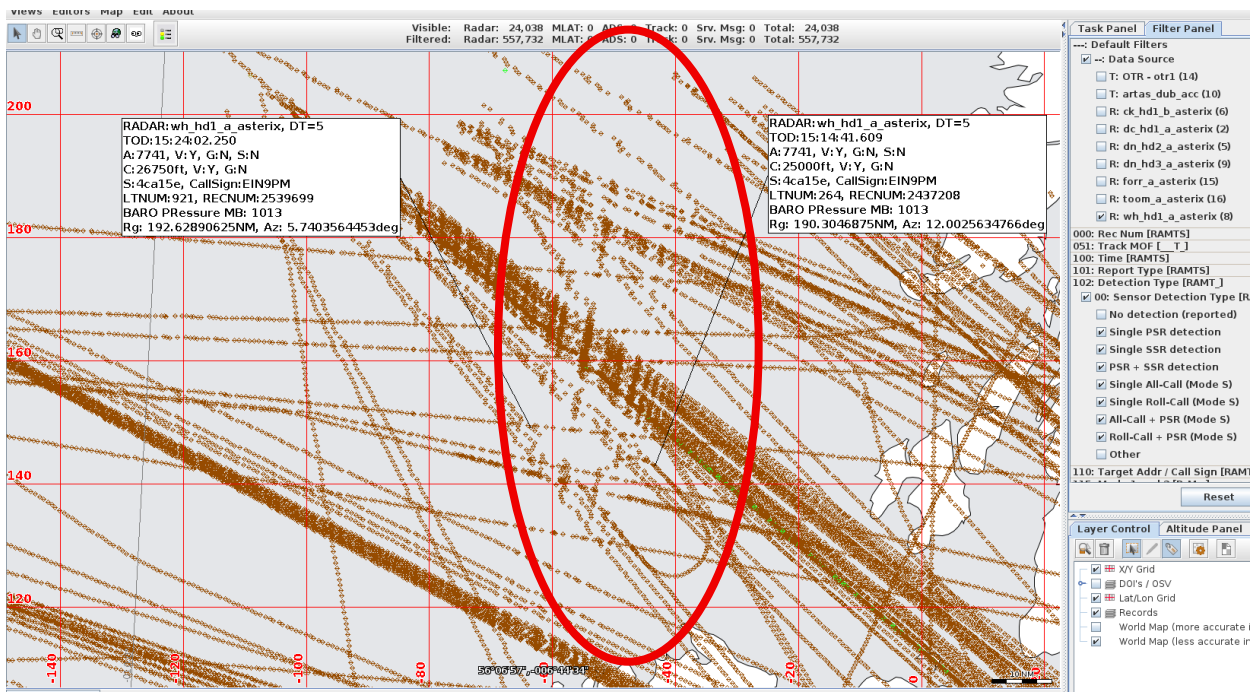
**Figure 2: North section of Woodcock Hill coverage 15/3/2025.**

In figure 2, we view 9,411 measured aircraft tracks to the North of Woodcock Hill within the 500,000+ tracks in this recording of 15 March 2025. The deflection and shadow effect of the mast at 7 degrees can be clearly seen in the red section highlighted. This effect which is seen across many different aircraft transiting through this radar bearing, is that the measured positions deviate from the actual straight-line trajectories and the distance between scanned updates is inconsistent with the constant velocity of the aircraft, which appear as gaps or jumps in the trajectories.



**Figure 3: North of Dooncarton coverage 15/3/2025.**

Figure 3 shows the same traffic viewed from Dooncarton Radar with no beam deflection as there is no structure deflecting the Radars measurement the Aircraft positions.

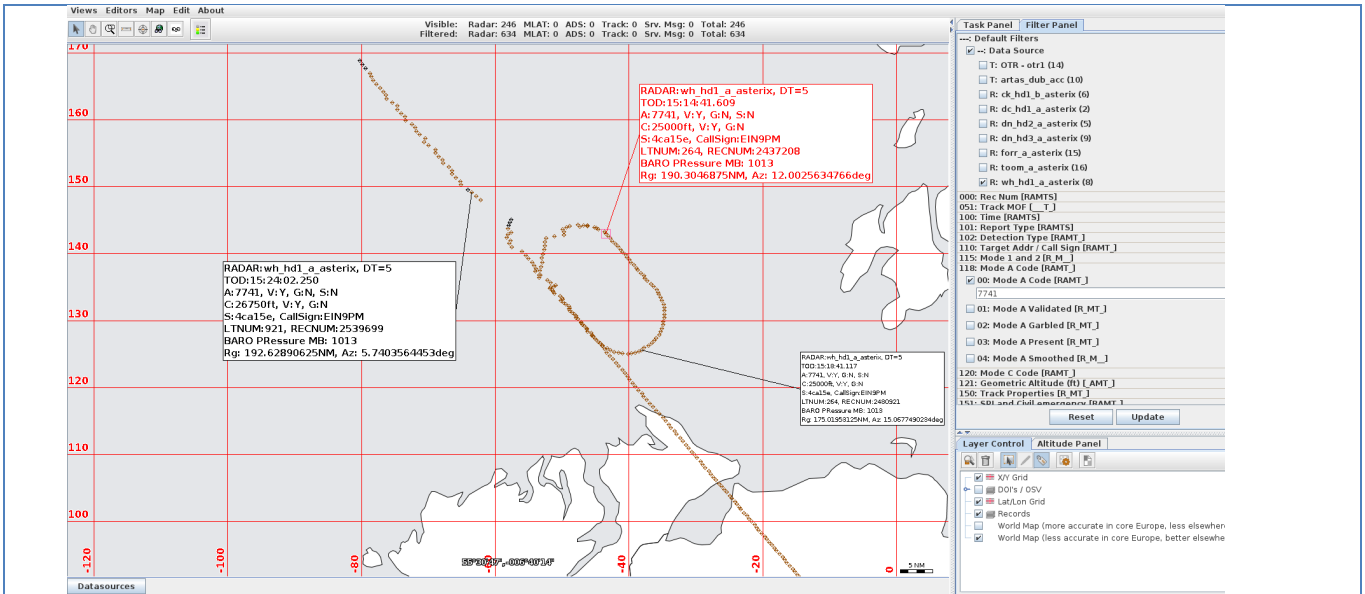


**Figure 4: North section of Woodcock Hill coverage 12/6/2025.**

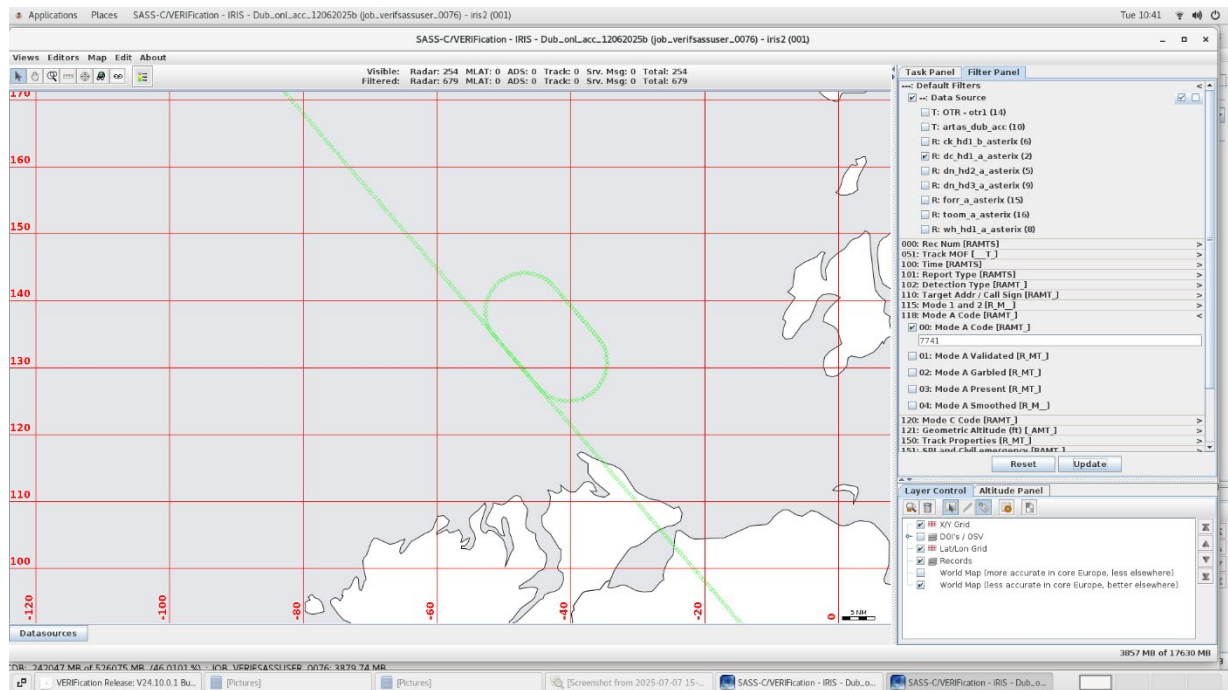
In figure 4 we view 24,000+ measured aircraft plots to the North of Woodcock Hill within the 500,000+ tracks in this recording of 12 June 2025. The deflection and shadow effect of the mast at 7 degrees can be clearly seen in the red section highlighted. Again, the effect which is seen across many different aircraft transiting through this radar bearing, is that the measured positions deviate from the actual straight-line trajectories and the distance between scanned updates is inconsistent with the constant velocity of the aircraft, which appear as gaps or jumps in the trajectories.

### Effect on individual aircraft

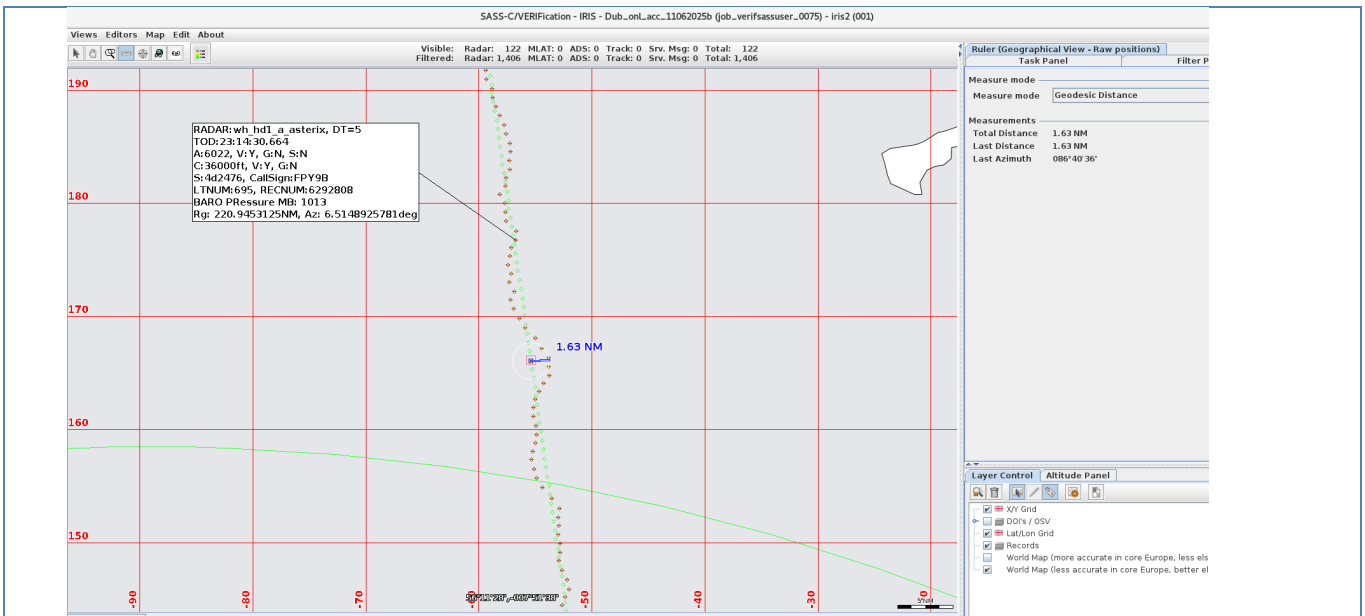
The screen shots in figures 4, 5 and 6 below show the effect of the obstacle at 7 degrees on individual aircraft. The most profound effect is on aircraft flying radials to the radar as these aircraft are effected for the longest duration.



**Figure 4:** This is an individual aircraft in a hold turn, there is significant deviation and lost plots as the aircraft transit behind the 30m mast.



**Figure 5:** Shown here is the same Aircraft as figure 4 from Dooncarton radar with no plot wander or detection issues.



**Figure 6:** This aircraft at FL360 or 36000 feet North of Donegal at azimuth 6 to 8 Degrees and a range of 170 to 230 Nm from the Woodcock Hill radar. There is a plot wander of 1.63 Nm or 3000 meters from actual horizontal position, the mandatory accuracy for 5 Nm separation is 550 meters and recommended is 330 meters.

The examples of aircraft in figures 2 to 6 are typical of all aircraft transiting this airspace behind the obstruction and at ranges greater than 150 Nms.

We have mitigated for the above deflections from the individual mast by implementing non-initialisation-areas in our Tracking systems (ARTAS). However, this non-initialisation-area mitigation must be kept to a minimum to avoid introducing holes in radar coverage.

## Anticipated radar impact of Ballycar and Oatfield wind Turbines

### Deflections:

We have clearly seen the evidence of radar signal deflections from a 30m mast at 730m from Woodcock Hill. It is reasonable to infer that each of the 12 proposed Ballycar wind turbines which are 156m high at 2.5-4km from the woodcock hill radar will also introduce radar signal deflections resulting in aircraft position errors and ATC alarms. For comparison the turbines proposed are over 5 times as large as the mast and at approximately 3.5 times the distance. Implementing non-initialisation-areas in our Radar Tracking systems for the Ballycar wind turbines would render up to 35-degree wide sector (at bearings from 70 to 105 degrees) of radar coverage from Woodcock hill unusable.

Similarly, we are also concerned that 26 Wind turbines of 180m height at 5-9km from the radar will also introduce bearing errors in the radar's measurements. Implementing non-initialisation-areas in our Radar Tracking systems for the Oatfield wind turbines would render up to 60-degree wide sector (bearings from 349 to 50 degrees) of radar coverage from Woodcock hill unusable.

The examples of the deviation of plots on Woodcock Hill radar are from a single static tower, 30 meters in height. The effect of larger dynamic structures will make mitigations very unpredictable and difficult to supply the required assurance under our safety management processes. It will be extremely difficult to assure that every possible scenario, turbine direction, parking position and aircraft traffic pattern has been considered.

**Reflections:**

Radar Reflections generate dual aircraft tracks which set off ANI automation system (COOPANS) safety-net alarms such as Short-Term Conflict Alert (STCA) and Duplicate (DUPE) alerts. These alerts distract Air Traffic controllers who may attempt to deconflicting real Air traffic tracks from tracks that do not physically exist. Each Safety Net Alarm initiates a safety occurrence report. Reflections occur when an aircraft replies to both a radar interrogation directly and to an interrogation reflected by the Turbine tower or rotor blade; the radar generates both a real aircraft track and a false reflected track in the direction of the turbine.

Developer commissioned radar Impact assessment reports have claimed that the potential impact of wind Turbines in regard to radar reflections is not significant and can be managed by AirNav Ireland. However, this does not take account of the particular scenarios of aircraft track initiation and emergency code management. Radar reflection processing removes aircraft replies which have a high probability of being reflections i.e. they have the same code as the real aircraft but are further away. For certain Aircraft codes, Emergency, Hijack, Comms failure and Conspicuity codes (A1000, A,2000 and A7000) reflection processing must not suppress duplicated aircraft tracks in order to ensure ATC can see when more than one aircraft in the airspace is squawking an emergency code. With no anti-reflection processing of emergency codes wind turbines within the safeguarding zones would increase the probability of multiple reflections of aircraft in emergencies being presented to ATC.

Another issue is true Mode-S reflections, this occurs where first radar contact with an aircraft is via a reflector, the real aircraft is suppressed and not visible by the radar due to transponder lockout function until 18 seconds after the last rollcall via the reflection. These have been reported on occasion with reflections from control towers or other significant reflectors in the vicinity of the radar.

**Shadowing:**

Shadowing from lattice masts results in a degradation of the probability of detection of aircraft flying behind the proposed turbines. This may result in the radar not meeting its mandated Surveillance performance requirements.

Developer radar Impact assessment reports have claimed that the potential impact of wind Turbines in regard to Shadowing is not significant and is limited to a short range behind the turbines which can be managed by AirNav Ireland.

Following discussions with Wind Turbine radar safeguarding experts in NATS UK, the limited range and impact of shadowing is only true when the wind turbine is below the level of the radar. In those cases, the shadow extends to the ground relatively close in range to the turbine. However, where the turbine is at the same level or higher than the radar the shadow extends to the end of radar range. It is also worth noting that NATS UK radar safeguarding zones extend to 28 km from the radar rather than 16km for AirNav Ireland.

**Airspace impacted:**

The area potentially impacted by Ballycar and Oatfield developments over the east coast is complex airspace with aircraft climbing from Terminal Manoeuvring areas to En-Route Airspace, in addition to aircraft being acquired as they enter Woodcock hills radar coverage from UK airspace. Radar position deviations in more complex airspace may increase the number of false target reports when compared to the less complex airspace to the West of Woodcock hill. If the level of false target reports and falsely confirmed reports exceed the recommended level this effects the ability of the system to support 3 and 5 Nm separation.

**Conclusion**

**AirNav requires evidence that wind turbines deployed within comparable ranges (2.5-4km Ballycar and 5-9km Oatfield) and in view of an En-route secondary radar have not impacted the surveillance performance of that radar.** This is in line with all our changes which require test and validation evidence for AirNav and IAA regulatory approvals. We have communicated this requirement for in-service evidence consistently in our meetings with the Wind farm developers.

Radar deflections, reflections and shadowing by wind turbines within the safeguarding zones all remain a concern for AirNav Ireland.

## Appendix C - Knockshanvo Windfarm Mitigation Options

# Knockshanvo Windfarm

## Radar Mitigation Options

AI Bridges

15 April 2026

CL-6005-RPT-005 v3.1

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## Change History Record

Issue	Change Reference	Date	Details
1.0	Initial Issue	12/12/2023	Initial Issue
2.0 (Draft)	Updated to include additional sections	19/03/2026	Draft
3.0	Updated to include client comments	14/04/2026	Issued
3.1	Minor text update	15/04/2026	Issued

## Executive Summary

Cyrrus was requested by AI Bridges to provide Aviation support for the Knockshanvo Windfarm proposal.

Previously in September 2021, Cyrrus published a report <sup>[1]</sup> providing the technical evidence that the proposed Violet Hill windfarm with 18 turbines would have Line of Sight with the Shannon Airport and Woodcock Hill radars. Following third-party engagements between key stakeholders, the project design evolved over time into the current 9-turbine project layout. A number of wind farm design changes occurred which ultimately resulted in the site reducing in scale from 18-turbines to the final proposed 9 turbine layout for which permission is being sought.

The previously proposed Violet Hill windfarm with 18-turbines has now been renamed as the Knockshanvo Windfarm with the number of turbines reduced to 9. In December 2023, Cyrrus published a report<sup>[4]</sup> providing updated technical evidence.

The report concluded that **no mitigation was required** for either the Shannon Airport or Woodcock Hill Monopulse Secondary Surveillance Radar systems. The Shannon Airport Primary Surveillance Radar may require mitigation.

In October 2024, AirNav submitted a response to the applicant's submission:

*" The proposed windfarm development would have a significant negative impact on the performance of the radar surveillance systems at our Woodcock Hill facility. The proximity and scale of the proposed development would lead to radar beam deflections, reflections, and shadowing from the wind turbines and there are no credible and implementable mitigations that could be applied to the Woodcock Hill radar to eliminate these effects. This development would compromise the Woodcock Hill radar's compliance with EU mandated surveillance performance criteria required "*

Cyrrus provided updates to address the concerns raised by AirNav in October 2024.

Wind turbines can cause clutter to Air Traffic Control displays, because older generations of Primary Surveillance Radar cannot distinguish between aircraft and wind turbines. More modern radar systems have options to use advanced processing techniques or other means to discriminate between these types of targets.

Monopulse Secondary Radar Systems (MSSR) (also known as cooperative sensors) work by transmitting a series of pulses to the Aircraft. The Aircraft will receive these pulses using a transponder. The transponder will then decode this series of pulses and transmit a response on a separate frequency. The Radar will receive this response and use the information in the Surveillance Data Processor to display the aircraft position, height etc on the Air Traffic Controllers display. As MSSR systems require two frequencies to operate they are not as vulnerable to problems from the wind turbines.

There are some common problems which can occur when wind turbines are sited near to radars. Table 1 uses a traffic light system to highlight the mitigation available for the Shannon Airport and Woodcock Hill radars which should allow them to operate alongside the proposed Knockshanvo windfarm.

Issue	Mitigation	Operationally Acceptable
<b>Shannon Airport MSSR</b>		<b>Y / N</b>
Reflections	The Thales RSM970 MSSR Sited at Shannon Airport is 18.4 km from the nearest wind turbine. Eurocontrol recommend that MSSR systems should be assessed if turbines are within 16 km of the radar. The fact Shannon Airports MSSR is outside the assessment zone, along with the evidence that the Thales system has inbuilt adaptive reflection processing, referenced in The Thales RSM970 MSSR Technical Description Document <sup>[2]</sup> , gives assurance the radar can work alongside the wind turbines. The radar utilises a two-stage system to remove both temporary (Dynamic) and permanent (Static) reflections from the system.	Y
Deflections	Although no assessment is necessary, The Thales RSM970 MSSR uses a well-established processing system to remove any False Replies Unsynchronised In Time (FRUIT). This process removes the issue of deflections from the system.	Y
Shadowing	The Shannon Airport radar is beyond the Eurocontrol wind turbine assessment zone. Any Shadowing from the Turbines would be minimal and have no Operational effect.	Y
<b>Woodcock Hill MSSR</b>		
Reflections	The Thales RSM970 MSSR Sited at Woodcock Hill is 5.6 km from the nearest wind turbine. The Thales radar utilises a two-stage system to prevent both temporary (Dynamic) and permanent (Static) reflections being displayed. It also has inbuilt adaptive reflection processing. This is referenced in The Thales RSM970 MSSR Technical Description Document <sup>[2]</sup> . To prevent possible reflection issues, some minor optimisation may be required. This is usually carried out as part of the scheduled maintenance of the equipment.	Y
Deflections	The Thales RSM970 MSSR uses a well established processing system to remove any False Replies Unsynchronised In Time (FRUIT). This process removes the issue of deflections from the system. No additional optimisation is required as a DEFRUITER is part of the standard MSSR processing on the Thales system.	Y
Shadowing	Due to the close proximity of the Turbines to the Woodcock Hill radar, some shadowing will occur. A detailed previous assessment was completed by Cyrrus on the previous 18-turbine design. It was considered any shadowing would be minimal and be	Y

	operationally tolerable. With the reduction in turbines to 9, it is assumed the shadowing would be no worse than the previous assessment and so remain operationally tolerable.	
Enroute Degradation	As the area affected is immediately behind the windfarm and only at very low levels, there will be no degradation to the enroute performance of the radar.	Y
<b>Shannon Airport PSR</b>		
Clutter caused by turbine blades	The Shannon Airport Thales STAR2000 radar was designed to operate in areas with wind turbines. Over the last 10-years, several improvements have been made to the processing systems used to prevent unacceptable clutter being caused by wind turbines. Some optimisation of the current radar may be required. This should be assessed by Thales and, if required, they can provide a series of staged upgrades to address this issue.	Y
Desensitisation of radar	As above, Thales could assess if optimisation or upgrades would be required to address any desensitisation issues.	Y

**Table 1: Radar Issues and Mitigation solutions**

Since 2021, Cyrrus have worked on several projects involving Thales STAR2000 Primary Surveillance Radars. The STAR2000 as used at Shannon Airport is a solid-state S-band radar designed to be windfarm tolerant. Thales has completed several dedicated impact studies of STAR2000 systems working successfully in areas with multiple wind turbines.

Cyrrus recommend that a survey be carried out on the Shannon Airport STAR2000 radar system to confirm its suitability to provide an operationally acceptable radar picture once the turbines are built. The survey will be an opportunity to clarify and formally define the ATC User Requirements for the associated Airspace.

The radar mitigation solution may not require an upgrade. Thales may determine the existing radars capability includes sufficient wind turbine filtering. If required system optimisation or upgrades are available to maximise the radar’s ability to comply with the ATC User Requirement. Thales has a suite of upgrade packages ranging from simple software updates to full system refresh’s depending on the systems current configuration.

Due to the radar’s modular system architecture, if upgrades are required on the Shannon Airport Primary Surveillance Radar, it is likely any downtime would be minimal. Thales have confirmed they have completed many projects of this type using tried and tested transition plans to allow the systems to remain operational throughout.

The erection of 9-wind turbines at the proposed Knockshanvo windfarm would have no operational impact on the Shannon Airport and Woodcock Hill MSSR systems. If upgrades are required to the Shannon Airport Primary Surveillance Radar, these should be completed before the windfarm is built. Any effect from the windfarm on the operational picture should have minimal effect. Should the

Woodcock Hill radar require optimisation, this would be completed one channel at a time and allow the system to remain operational throughout.

In Summary, both the Shannon Airport and Woodcock Hill radars could Mitigate against adverse effects caused by the proposed Knockshanvo 9-turbine windfarm.

## Abbreviations

MSSR	Monopulse Secondary Surveillance Radar
NM	Nautical Miles
PSR	Primary Surveillance Radar
RDP	Radar Data Processor
RLoS	Radar Line of Sight

## References

- [1] Cyrrus - CL-5693-RPT-002 v1.0 Violet Hill Wind Farm Radar Assessment
- [2] EUROCONTROL Guidelines for Assessing the Potential Impact of Wind Turbines on Surveillance Sensors – GUID-0130 – 9/9/2014
- [3] Thales STAR2000 datasheet – 1/1/2014
- [4] Cyrrus - CL-6005-RPT-002 v2.0 Knockshanvo windfarm mitigation options – 2024
- [5] EUROCONTROL Specification for ATM Surveillance System Performance (Volume 1) – 21/03/2024

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## 1. Introduction

### 1.1. Background

- 1.1.1. In September 2021, Cyrrus published a report <sup>[1]</sup> providing the technical evidence that the proposed Violet Hill windfarm with 18 turbines had Radar Line of Sight with the Shannon Airport and Woodcock Hill radars.
- 1.1.2. Following third-party engagements between key stakeholders the project design evolved over time into the current 9-turbine project layout. Several wind farm design changes occurred during this time, which ultimately resulted in the site reducing in scale from 18-turbines to the final proposed 9-turbine layout for which permission is being sought. In December 2023, Cyrrus published a report <sup>[4]</sup> providing updated technical evidence. The Shannon Airport Monopulse Secondary Surveillance Radar system is beyond the 16 km assessment zone recommended by Eurocontrol <sup>[2]</sup> so does not require an assessment. However, the ANSP can extend this range for any turbine within Line of Sight provided there is a reasonable rationale. AirNav have expressed concern over the impact to the Shannon MSSR, an assessment is now included in the report.
- 1.1.3. In Europe, several countries e.g. Belgium, France and the Netherlands now rely on MSSR assessments being done by TNO using a proven methodology. The results are used by the respective ANSP's to assess the operational impact (if any). This robust process is used to approve windfarm developments with conditions if applicable.
- 1.1.4. The Woodcock Hill Monopulse Secondary Surveillance Radar is 5.6 km from the nearest turbine. The previous reports <sup>[1 & 4]</sup> concluded that any shadow region beyond the proposed turbines would be sufficiently small to be operationally tolerable. This conclusion is now supported by the TNO technical report in Appendix G {as shown in the response statement} and, our assessment of Operational impact based on Airspace Utilisation. Nevertheless, only AirNav has the authority to undertake the operational impact assessment.
- 1.1.5. Shannon Airport Primary Surveillance Radar has Radar Line of Sight to the wind turbines at Knockshanvo and, it is likely it will require some mitigation. AirNav Ireland has contracted Thales to upgrade the STAR2000 at Shannon Airport to the latest STAR NG model. While it is difficult to define the exact capability of the STAR NG to windfarm filtering, it may be sufficient to address PSR clutter from the Knockshanvo wind turbines. AirNav should be able to confirm if this is the case.
- 1.1.6. If either the PSR or SSR at Shannon Airport requires mitigation, this could be provided by additional sensors with a proven operational history. Such sensors would not be manufactured by Thales and, AirNav have stated they will only purchase from Thales. This could be resolved by suitable commercial arrangements.
- 1.1.7. If required a mitigation scheme is available for both the Shannon Airport PSR and Woodcock Hill SSR, though the exact solution will require further engagement with AirNav.

## 2. Overview

### 2.1. Knockshanvo Windfarm

2.1.1. The previously proposed Violet Hill windfarm with 18-turbines has now been renamed as the Knockshanvo Windfarm with the number of turbines reduced to 9.

2.1.2. Table 2 details the turbine positions for the Knockshanvo windfarm. Figure 1 shows the positions.

Label	X_ITM	Y_ITM	Latitude	Longitude
T01	553306.444	669419.531	52.77379	-8.69201
T02	553421.846	670076.257	52.7797	-8.6904
T03	553812.149	669850.553	52.7777	-8.68458
T04	556212.277	669444.129	52.77425	-8.64895
T05	556662.506	670000.996	52.77929	-8.64236
T06	556896.229	669600.869	52.77571	-8.63884
T07	556727.353	669042.335	52.77068	-8.64127
T08	558463.188	669913.098	52.77864	-8.61566
T09	558864.227	669556.784	52.77547	-8.60967

Table 2: Knockshanvo Turbine Positions

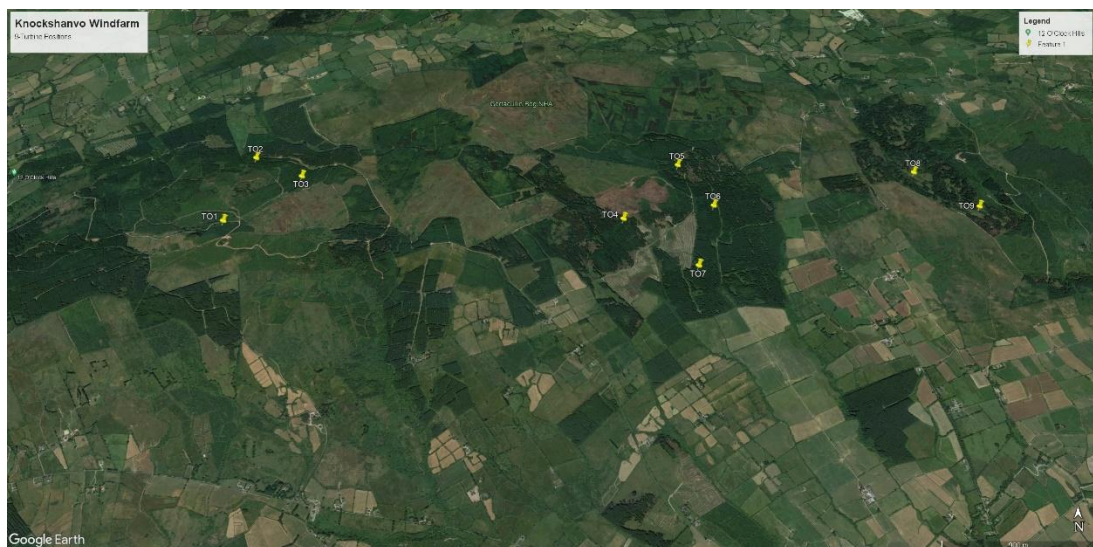


Figure 1: Knockshanvo Turbine Positions

2.1.3. The windfarm is 18.4 km from the Shannon Airport Primary Surveillance Radar with co-mounted Monopulse Secondary Surveillance Radar. Section 2.2 covers common issues which can occur when wind turbines are sited in close proximity to radars.

## 2.2. Common Issues

2.2.1. All radar systems can suffer from problems when working alongside windfarms. Table 2 below details the most common issues, and how they can be mitigated using the current systems.

Issue	Mitigation	Operationally Acceptable
<b>Shannon Airport MSSR</b>		<b>Y / N</b>
Reflections	The Thales RSM970 MSSR Sited at Shannon Airport is 18.4 km from the nearest wind turbine. Eurocontrol dictate that MSSR systems should be assessed if turbines are closer than 16 km. This, along with the fact the Thales system has inbuilt adaptive reflection processing. In common with similar systems, the Thales RSM970 radar utilises a two-stage system to prevent both temporary (Dynamic) and permanent (Static) reflections being displayed.	Y
Deflections	Although no assessment is necessary, The Thales RSM970 MSSR uses a well-established processing system to remove any False Replies Unsynchronised In Time (FRUIT). This process removes the issue of deflections from the system. Although ANSP's have not considered this as an issue, AirNav advised they have concerns in this area. These concerns are addressed in the TNO report.	Y
Shadowing	The Shannon Airport radar is beyond the Eurocontrol wind turbine assessment zone. Any Shadowing from the Turbines would be minimal and have no Operational impact.	Y
Enroute Degradation	As the area affected is immediately behind the windfarm and only at very low levels (1500ft), there will be no degradation to the enroute performance of the radar.	Y
<b>Woodcock Hill MSSR</b>		
Reflections	The Thales RSM970 MSSR Sited at Woodcock Hill is 5.6 km from the nearest wind turbine. Eurocontrol dictate that MSSR systems should be assessed if turbines are closer than 16 km. This, along with the fact the Thales system has inbuilt adaptive reflection processing. In common with similar systems, the Thales RSM970 radar utilises a two-stage system to prevent both temporary (Dynamic) and permanent (Static) reflections being displayed.	Y

Deflections	Although no assessment is necessary, The Thales RSM970 MSSR uses a well established processing system to remove any False Replies Unsynchronised In Time (FRUIT). This process removes the issue of deflections from the system. Although ANSP's have not considered this as an issue, AirNav advised they have concerns in this area. These concerns are addressed in the TNO report.	Y
Shadowing	Due to the close proximity of the Turbines to the Woodcock Hill radar, some shadowing will occur. A detailed previous assessment was completed by Cyrrus on the previous 18-turbine design. It was considered any shadowing would be minimal and be operationally tolerable. With the reduction in turbines to 9, it is assumed the shadowing would be no worse than the previous assessment and so remain operationally tolerable.	Y
<b>Shannon Airport PSR</b>		
Clutter caused by turbine blades	The Shannon Airport Thales STAR2000 radar was designed to operate in areas with wind turbines. Over the last 10-years, several improvements have been made to the processing systems that are now incorporated into the STAR NG. As noted above, it is understood the Airport has contracted Thales to upgrade the radar to a STAR NG with the new system benefiting from these improvements.	Y
Desensitisation of radar	As above, it is understood the Airport radar will be upgraded to a STAR NG.	Y

**Table 3: Radar Issues and Mitigation solutions**

2.2.2. Sections below provide detail on the Shannon Airport and Woodcock Hill radar systems and the likelihood of them being able to comply with the Operational Requirements in the presence of the proposed 9-Turbine Knockshanvo Windfarm.

### 3. MSSR

#### 3.1. Shannon Airport



Figure 2: Shannon Airport PSR with co-mounted MSSR

3.1.1. Figure 3 shows the location of the Shannon Airport radar in relation to the Windfarm. The distance between the radar and the nearest turbine is 18.4 km. Therefore, the Shannon Airport MSSR is beyond the 16 km assessment zone recommended by Eurocontrol [2].

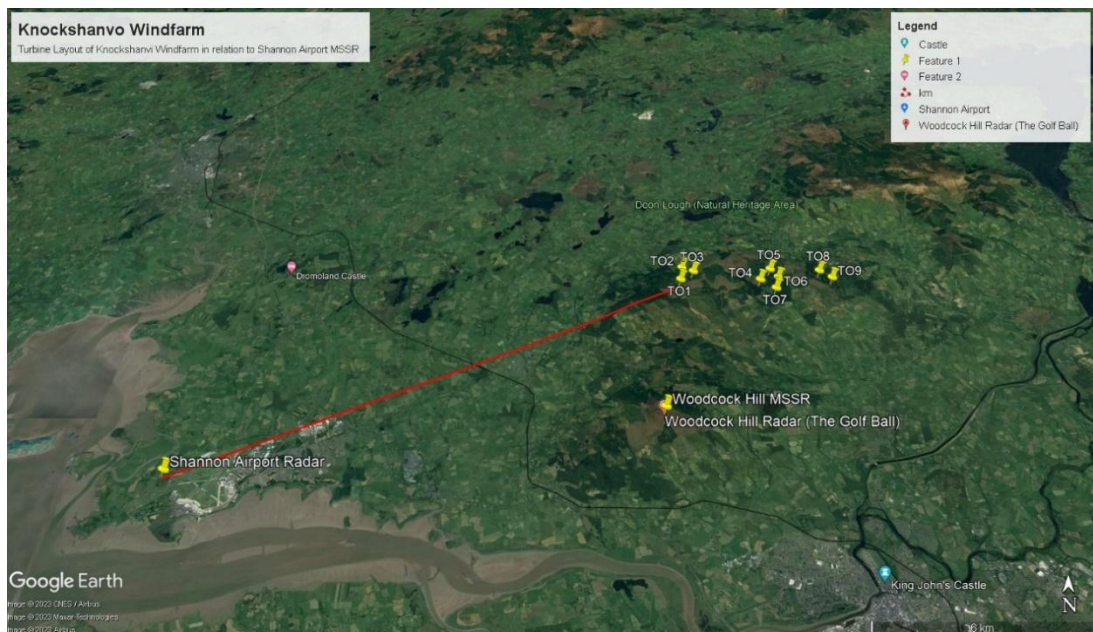


Figure 3: Shannon Airport Radar to Knockshanvo Windfarm

3.1.2. To confirm Line of Sight (LoS) between the radar and the wind turbines the HTZ Communication tool by ATDI was used. Figures 4 and 5 show that LoS exists to the nearest and furthest turbines. All turbines have been assessed and found to have LoS.

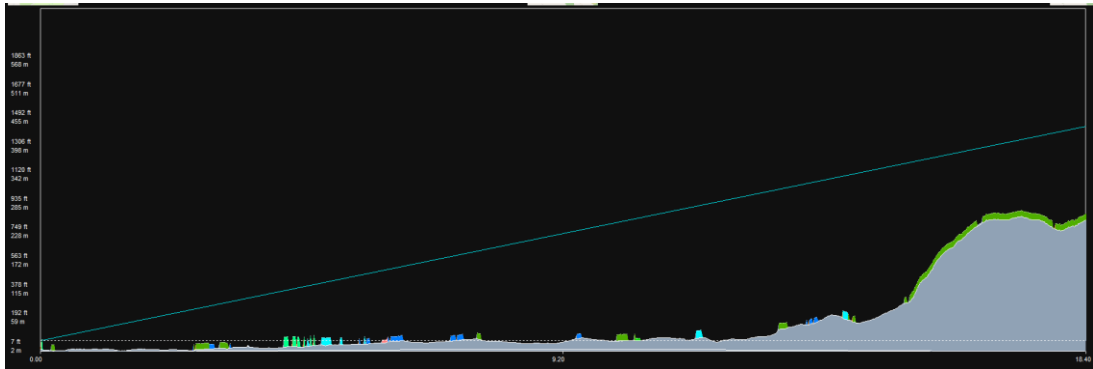


Figure 4: LoS from Shannon Airport Radar to the Nearest Turbine.

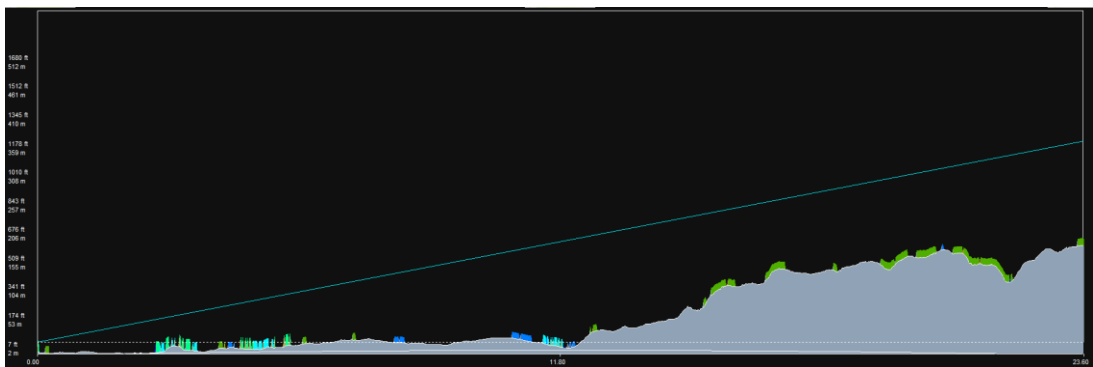


Figure 5: LoS from Shannon Airport Radar to the Furthest Turbine

### 3.2. Woodcock Hill



Figure 6: Woodcock Hill MSSR system

3.2.1. Figure 7 shows the location of the Woodcock Hill radar in relation to the Windfarm. The distance between the radar and the nearest turbine is 5.6 km. Eurocontrol recommend an

impact assessment be completed for turbines closer than 16 km. This has been completed by TNO, see Appendix G {As shown in the response statement}.

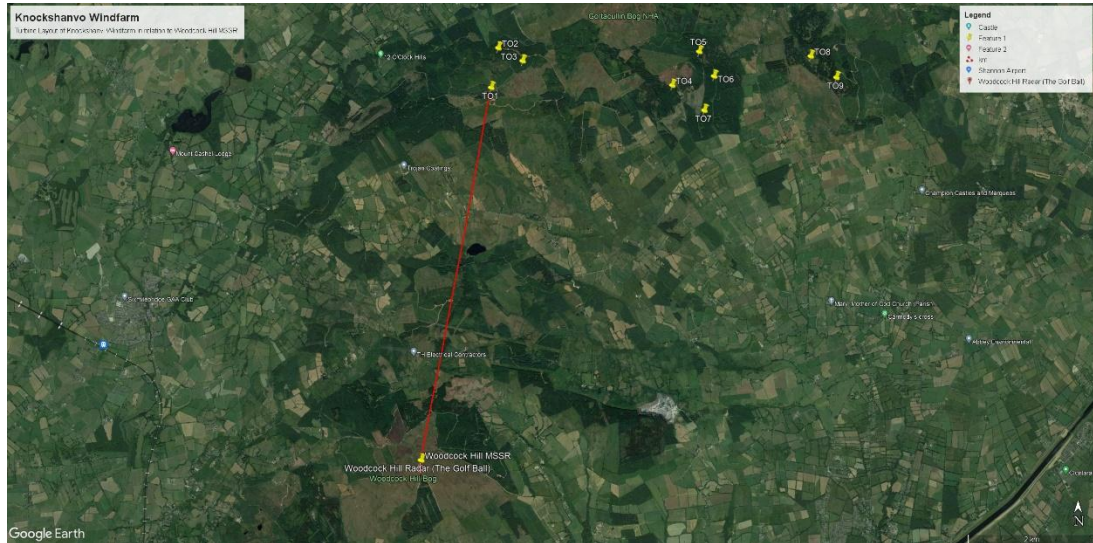


Figure 7: Woodcock Hill M SSR in relation to the proposed windfarm

- 3.2.2. The rationale behind the Eurocontrol assessment is to ensure the Operational impact is acceptable or that a suitable mitigation is in place to ensure continued compliance.
- 3.2.3. The previous Cyrrus reports [1 & 4] stated that the turbines could impact radar performance. The Operational impact has been considered using the technical analysis from TNO.
- 3.2.4. To confirm the radar has Line of Sight with the turbines, the HTZ Communication tool by ATDI was used. Figures 8 and 9 show that LoS exists to the nearest and furthest turbines. All turbines have been assessed and found to have LoS.

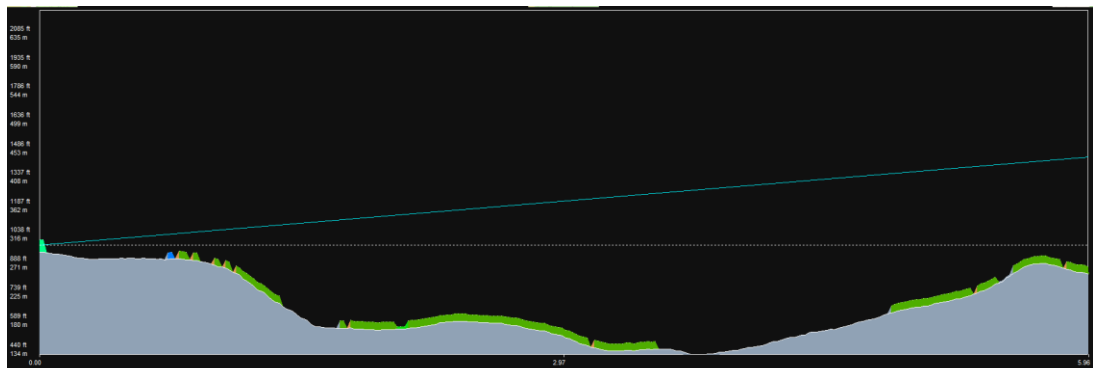


Figure 8: LoS Woodcock Hill M SSR and TO1

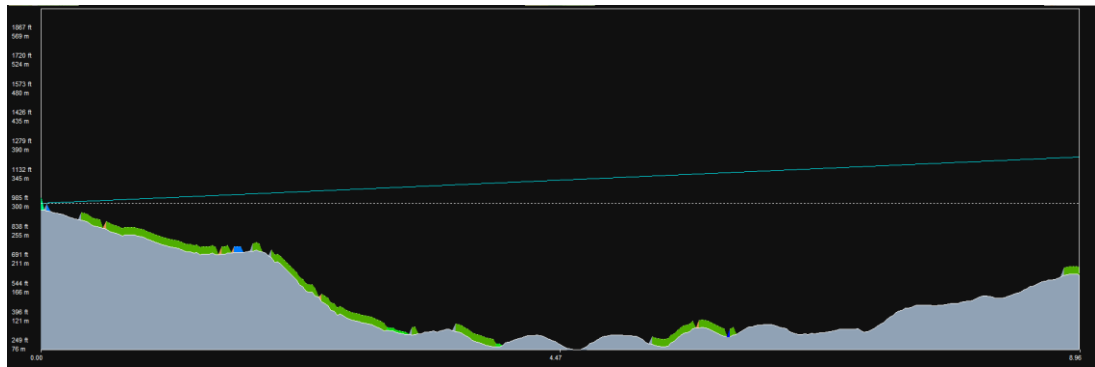


Figure 9: LoS Woodcock Hill to TO9

## 4. PSR

### 4.1. Overview of PSR

4.1.1. Wind turbines can impact Primary Surveillance Radars (PSR) performance, as their processing algorithms can 'see' turbine blades as moving targets and display them as clutter to ATC. Modern Surveillance Data Processing systems use advanced techniques prevent this clutter from the Wind turbines from being displayed on the ATC Controllers Display.

### 4.2. Shannon Airport PSR

4.2.1. The Shannon Airport PSR is a Thales STAR 2000 PSR installed in 2011 / 12. The system was designed to work in coverage volumes containing wind turbines. For a relatively small windfarm within the radar's coverage volume, the turbines should have a minimal impact on performance. While this was previously mentioned in Thales brochures, these are no longer available.

4.2.2. Thales has a suite of optimisation and upgrade packages available for the STAR2000. It is understood the Shannon Airport radar is being upgraded to STAR NG specification which will further enhance the STAR 2000 capabilities to filter the turbines at Knockshanvo and elsewhere.

4.2.3. Thales state that they have a mature transition framework which allows system upgrades and optimisation to be implemented without the requirement for long periods of operational downtime. Cyrrus has experience of working with Airports and ANSPs to produce Transition Plans that minimise downtime, risk and comply with Safety Management Systems as required by regulators. If AirNav provide the timescales for the upgrade, the enhanced capability may be available prior to the erection of the wind turbines. To fully evaluate the transition the Operational Handover date of the STAR NG is required from AirNav.

### 4.3. Mitigation Options for Shannon PSR

4.3.1. The following suite of mitigation options including the detail required to achieve each option in terms of timescales, costs, risks, integration, implementation and downtime, validation testing, commissioning and transition, safety programme planning, management and production/ updates of safety assurance artefacts and regulatory assurance compliance.

4.3.2. Each mitigation option is also grounded in an evidence base that will determine whether the measure is applicable to Shannon PSR alongside examples of where it has been implemented at other airport radar installations.

4.3.3. If the Operational handover date for the STAR NG is later than the planned installation date of the turbines, it may be possible to do limited upgrades to the existing STAR 2000 as listed below.

- Option A: Thales software upgrade (applied to existing Thales STAR 2000)
- Option B: Hardware and software upgrade (applied to existing Thales STAR 2000)

- Option C: Add a Terma Scanter 4002 X-Band radar as a second sensor to complement the existing Thales STAR 2000
- Option D: Upgrade Shannon PSR to the latest Thales variant, STAR NG.
- Option E: Tender for new radar with windfarm mitigation capability (2d+ or 3D)

4.3.4. As mentioned previously, a collaborative approach is necessary with AirNav and Shannon Airport to determine the appropriate option for their operational circumstances:

4.3.5. This will enable all parties to develop key details for the delivery of the most appropriate option such as cost attribution, timescale, implementation plan, etc.

4.3.6. This will enable all parties to develop the final form of the Aviation WFMS. If no, move on to examine the next option.

4.3.7. Thales have confirmed that they have upgraded the STAR 2000 at the following airports, Schiphol, Newcastle, and in these examples the upgrades are being used to mitigate windfarm issues. At Newcastle the Thales PSR is used to mitigate to the south of the Airport with a Terma radar being used to mitigate wind turbines to the North. The UK MOD have purchased the Thales STAR NG with several being in area's surrounded by windfarms, therefore it is assumed the windfarm filtering capability is actively being used at these locations.

4.3.8. What is clear from a review of industry evidence is that Thales PSR equipment is being successfully operated at numerous airports globally to mitigate issues arising from windfarms and therefore it is technically incorrect to claim, as AirNav and Shannon Airport have maintained to date, that there are no mitigation measures available.

4.3.9. We also retain the option to install an alternative radar technology with proven windfarm mitigation capability if all Options are insufficient to address the concerns of AirNav and Shannon Airport. The alternative radar technology could include the Terma Scanter 4002 x-band radar being used as an infill over the windfarms or to provide 360-degree coverage for the first 40NM with coverage beyond 40NM being provided by the existing Thales PSR. The more expensive use of 2D+ or 3D technology as used by the military would also provide an acceptable mitigation solution. These technology options have been successfully implemented at multiple locations.

## 4.4. Mitigation Options for Woodcock Hill MSSR

### 4.4.1. Option 1 – Upgrade existing MSSR.

The existing MSSR could be replaced with MSSR system with suitable wind turbine mitigation. However, the mitigation is unlikely to resolve the concerns raised by AirNav Ireland relating to deflections. As Cyrrus do not believe these are caused by the MSSR itself, but it's implementation in the wider Surveillance System i.e. AirNavs Multi Radar Tracker using the MSSR beyond Eurocontrol's recommended limits in <sup>[5]</sup>.

### Option 2 – Short range supplementary MSSR.

As a supplementary MSSR would only need to provide coverage over Knockshanvo, equipment with less than 20NM would be more than adequate if sited correctly. Furthermore, with a range of less than 30NM it would cover adjacent windfarms and possibly those proposed for the future. This mitigation solution would require the new MSSR to be integrated into the AirNav MRT. If this is not accepted, other equipment could be installed to integrate the existing and new MSSR by providing combined data for use by Shannon Airport (No impact to En-Route Upper Airspace).

**Option 3 – Supplementary MSSR with extended range.**

While a supplementary MSSR with the normal equipment capability to provide 250NM coverage, at this range the antenna rotation rate would need to be slower. Consequently the 'update rate' would be non-compliant with Eurocontrol <sup>[3]</sup>. However, extending the distance to 80NM may be feasible, this would provide betterment to the existing AirNav Surveillance System.

**Option 4 – Wide Area Multilateration.**

While WAM could provide a solution for Knockshanvo and other proposed windfarms, AirNav has stated this would not be acceptable.

## 5. Operational Considerations

### 5.1. Airspace Overview

5.1.1. Aeronautical Charts are used by pilots to assist with navigation. They show the airspace boundaries and the associated radio frequencies for the responsible Air Navigation Service Provider (ANSP). The main purpose of a chart is to ensure the appropriate minimum safe altitudes, in the vicinity of a defined area around an aerodrome.

### 5.2. Operational Requirements

5.2.1. The Eurocontrol Surveillance Standard defines the surveillance requirements for aerodromes and terminal areas.

Radar Surveillance in En-Route Airspace and Major Terminal Areas	SUR.ET1.ST01.1000-STD-01-01
<b>5. OPERATIONAL REQUIREMENTS</b>	
<b>5.1 Coverage Requirements</b>	
<b>5.1.1 General</b>	
<b>5.1.1.1</b>	Comprehensive and continuous radar coverage of high quality and reliability shall be constantly available in order to achieve radar operational separations of 3 NM, 5 NM and 10 NM.
	<b>NOTE -</b> Those defects in the radar coverage which do not hinder the provision of radar services are acceptable, e.g. gaps.
<b>5.1.1.2</b>	Radar stations shall be sited so that the zenithal gap in the radar coverage is either contained within the coverage of an adjacent radar, or is located so that the zenithal gap does not reduce the operational effectiveness of the radar service.
<b>5.1.2 Major Terminal Areas</b>	
<b>5.1.2.1</b>	Duplicated secondary and single primary surveillance radar coverage shall be provided within major terminal areas. This combination assures the continuous availability of radar position information and enables provision of air traffic services to aircraft unable to respond to SSR interrogations.
<b>5.1.2.1</b>	The coverage within major terminal areas shall extend from the lowest altitudes of the intermediate approach segments for the principal aerodromes concerned. Coverage elsewhere will extend from the minimum levels at which radar services are required to be provided, up to the upper limit of the terminal area.
	<b>NOTE -</b> The coverage requirements below the lowest altitudes of the intermediate approach segments can be met in accordance with local aerodrome conditions, provided continuity of services for the major terminal area is ensured.
<b>5.1.2.3</b>	Provision shall be made for the continuity of radar coverage in the areas interfacing with en-route airspace.

Figure 10: Operational Requirement for Radar Surveillance in En-Route Airspace and Major Terminal Areas

### 5.3. Surveillance Requirements for Shannon Airport

- 5.3.1. Shannon Airport is within 18.4 km of the proposed Knockshanvo Winfarm Turbine 01, Figure 11 shows the ATC Surveillance Minimum Altitude Chart (SMAC) for the airspace around the proposed Knockshanvo Windfarm, with the location of Shannon Airport. A key feature of the SMAC is the minima for each Sector of airspace.
- 5.3.2. As shown in Figure 12, Sectors 1 – Inner Control Terminal Area and Sector 2 are pertinent to Shannon Airport operations with minimum surveillance altitudes of 2300ft and 3000ft Above Mean Sea Level (AMSL) respectively. These are the lowest altitudes that pilots can receive vectors from Air Traffic Control. It ensures safe flight altitudes for aircraft during approach when flying Instrument Flight Rules IFR). Solid radar surveillance at these altitudes avoids the need for procedural mitigation solutions.

### 5.4. En- Route Services

- 5.4.1. The En-Route ANSP for the Upper Airspace is also AirNav Ireland based at the Air Traffic Control Centre near Shannon Airport. Radar Surveillance coverage is required for Upper Airspace typically starting at 5,000ft. The Eurocontrol Surveillance Standard paragraph 5.2.1 states that:-

***Except as provided for in 4.2.2 and 4.2.3, in en-route airspace, duplicated SSR coverage shall extend both from the minimum cruising levels up to the highest IFR cruising levels, and where radar services are required to be provided. Exemptions are detailed in sub-paragraphs 4.2.2 and 4.2.3.***

***The horizontal extent of the coverage shall be to at least 30 NM beyond the area of responsibility of the relevant Area Control Centre (ACC), except where this is impossible to achieve due to geographical limitations.***

**NOTE** - Overlapping radar coverage in the areas of responsibility of adjacent air traffic control centres, or radar sharing, is a prerequisite for the systematic transfer of radar control of aircraft from one ACC to another while maintaining the required level of separation.

- 5.4.2. AirNav Ireland stated their requirement for SSR horizontal coverage to a range of 256NM with vertical coverage from ground level to the upper limit of the airspace. Due to curvature of the earth at maximum range, low level coverage is unlikely to be achieved below 35000ft, making it's Operational use very limited. This is further restricted due to the target position accuracy being +/- 800m making it unsuitable for use in MRT systems as stated in the Eurocontrol Guidance [Reference].

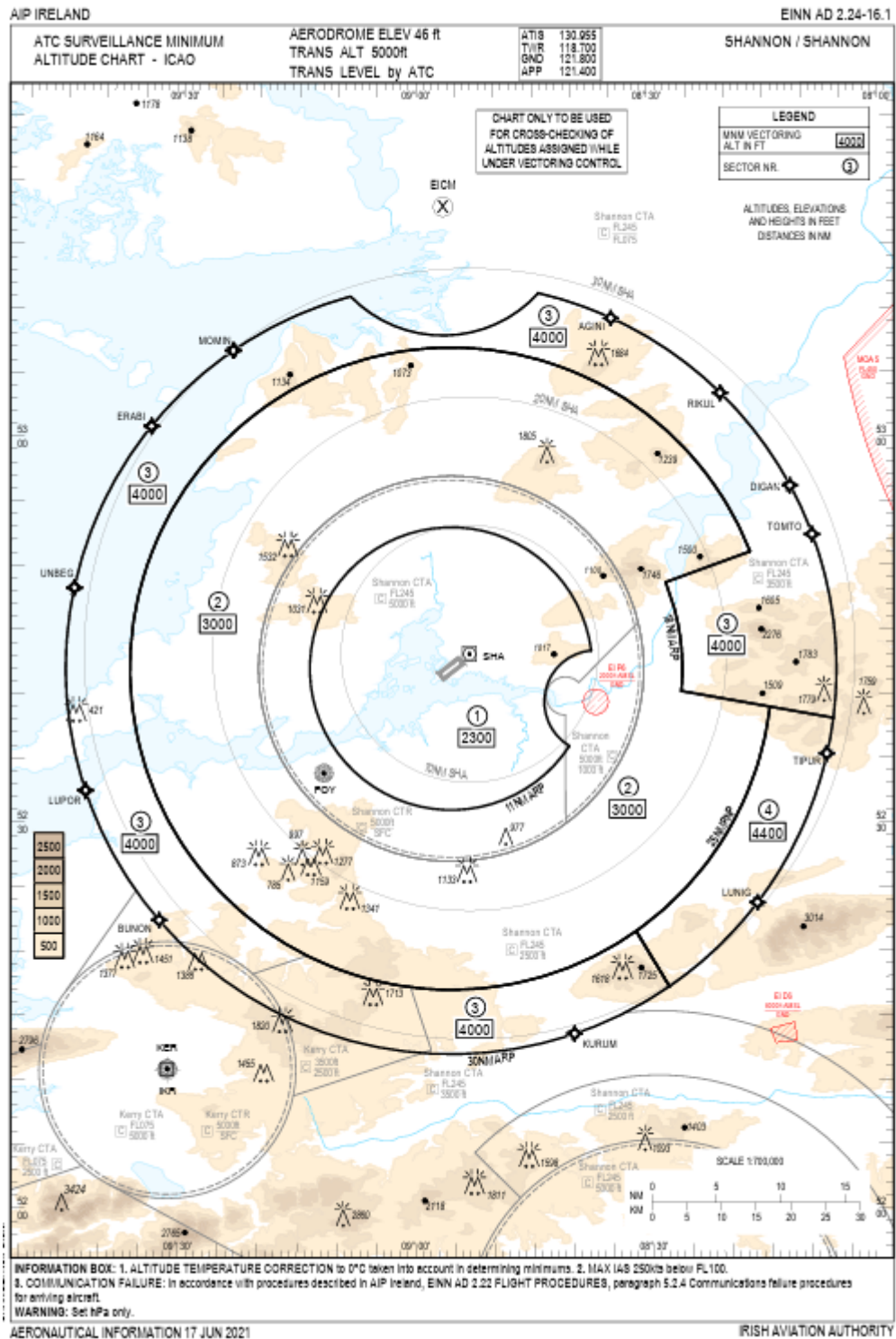


Figure 11: Shannon Airport ATCSMAC

EINN AD 2.24-16.2 17 JUN 2021	AIP IRELAND
<p><b>ATC Surveillance Minimum Altitude Coordinates</b></p> <p><b>Sector 1. MNM ALT 2300</b></p> <p>52°43'29"N 008°37'32"W, arc anti-clockwise 4 NM radius centre 52°39'30"N 008°36'59"W, 52°36'05"N 008°40'23"W, arc 11 NM radius centre 52°42'07"N 008°55'29"W, 52°43'29"N 008°37'32"W</p> <p><b>Sector 2. MNM ALT 3000</b></p> <p><b>Inner boundary:</b> 52°43'29"N 008°37'32"W, arc anti-clockwise 4 NM radius centre 52°39'30"N 008°36'59"W, 52°36'05"N 008°40'23"W, arc 11 NM radius centre 52°42'07"N 008°55'29"W, 52°43'29"N 008°37'32"W</p> <p><b>Outer boundary:</b> 52°51'06"N 008°17'04"W, 52°48'46"N 008°27'57"W, arc 18 NM radius centre 52°42'07"N 008°55'29"W, 52°40'19"N 008°26'03"W, 52°39'02"N 008°14'43"W, arc 25 NM radius centre 52°42'07"N 008°55'29"W, 52°51'06"N 008°17'04"W</p> <p><b>Sector 3. MNM ALT 4000</b></p> <p>52°38'06"N 008°06'38"W, 52°40'19"N 008°26'03"W, arc anti-clockwise 18 NM radius centre 52°42'07"N 008°55'29"W, 52°48'46"N 008°27'57"W, 52°51'06"N 008°17'04"W, arc anti-clockwise 25 NM radius centre 52°42'07"N 008°55'29"W, 52°21'40"N 008°32'00"W, 52°17'21"N 008°27'50"W, arc 30 NM radius centre 52°42'07"N 008°55'29"W, 53°11'03"N 009°08'26"W, arc anti-clockwise 10 NM radius centre 53°18'01"N 008°56'30"W, 53°11'18"N 008°44'11"W, arc 30 NM radius centre 52°42'07"N 008°55'29"W, 52°38'06"N 008°06'38"W</p> <p><b>Sector 4. MNM ALT 4400</b></p> <p>52°38'06"N 008°06'38"W, 52°39'02"N 008°14'43"W, arc 25 NM radius centre 52°42'07"N 008°55'29"W, 52°21'40"N 008°32'00"W, 52°17'21"N 008°27'50"W, arc anti-clockwise 30 NM radius centre 52°42'07"N 008°55'29"W, 52°38'06"N 008°06'38"W</p>	
AIRAC Amdt 006/21	IRISH AVIATION AUTHORITY

Figure 12: Aeronautical Chart covering area around proposed development

## 5.5. IFP Safeguarding and mitigation

- 5.5.1. Until Feb 2022, Cyrrus were approved Instrument Flight Procedure Designers, due to changes in EASA regulations maintaining our accreditation was no longer commercially viable. We remain accredited by the UK CAA and it remains a core part of our business. In common with other IFP designers in Europe and Worldwide, our designers comply with PANSOPS design criteria. While unable to undertake IFP design work in Ireland, we work closely with ASAP based in Slovakia who hold the required accreditation. For Safeguarding assessments, the IAA do not require accreditation. AirNav also have IFP designers that would confirm our Safeguarding assessments are valid.
- 5.5.2. Cyrrus delivered a report [IFP Safeguarding Report, CL-6049-RPT-003 v1.1, 24 May 2024] with four options for changing the Shannon IFPs and Airspace to accommodate the proposed wind farm. A further report containing ATCSMAC Design Options CL-6049-RPT-006 v1.0 was delivered by Cyrrus. Option A keeps the SMA for Sector 1 while the remaining options require a higher SMA of 2,600ft and a change to the airspace boundary. An extract from the report is provided below:

**Mitigation Options**

The mitigation options listed below are for the Airport to consider, this will be subject to their Safety Management System (SMS) requirements and the commercial benefit of accepting the mitigation.

1. Raise the applicable MOCA or PDG of the affected procedures, this option will be for the airport to consider.
  - a. SIDS (TOMTO3A, DIGAN3A, ABAGU3A) RWY06, increase the obstacle clearance PDG from 3.3% to 3.9%
  - b. ILS OR LOC RWY 06, impact to the ILS CAT I MACG, increase in Obstacle Clearance Altitude / Height (OCA/H) required, or redesign of ILS procedure to include OCA/H for a 2.5% MACG and 3.0% MACG.
  - c. VOR RWY 24, Final Approach, increase MOCA from 1270ft to 1530ft, an additional Step-down fix (SDF) may be required to prevent an increase to the final approach gradient.
  - d. ATCSMAC increase Sector 1 Minimum Vectoring Altitude (MVA) from 2300ft to 2600ft, or redesign the ATCSMAC to reduce the size of Sector 1 but keep the remaining Sector 1 area at the existing 2300ft MVA.

Figure 13: IFP Safeguarding conclusions

- 5.5.3. The increase from 2,300ft to 2,600 ft for the Inner CTA for Options B, C and D would be unchanged or less challenging for radar surveillance systems. Therefore, the more demanding requirement is to ensure that there is solid radar coverage at 2,300ft.

IFP Safeguarding Option A		
1.	Horizontal Range	256NM

2.	Minimum Vertical Coverage at Knockshanvo Wind Farm	2,300ft AMSL
<b>IFP Safeguarding Option D</b>		
3.	Horizontal Range	256NM
4.	Minimum Vertical Coverage at Knockshanvo Wind Farm	2,600ft AMSL

Figure 14: Surveillance Requirements Summary Table

## 5.6. Surveillance Coverage Assessment

### 5.6.1. Vertical Coverage

5.6.2. Taking the highest wind turbine T03 as listed in the Cyrrus Safeguarding Report CL-6005-RPT-003 v2.0, and the calculated height of shadowing, Figure 15 shows that shadowing does not infringe the required MVA of 2,300ft for aircraft flying IFR.

Under the Rules of the Air, Aircraft flying VFR must avoid obstacles by 500ft vertically and horizontally. Therefore, no aircraft should be flying below 2000 ft. Figure 15 also shows that aircraft at this altitude would be outside the shadow area.

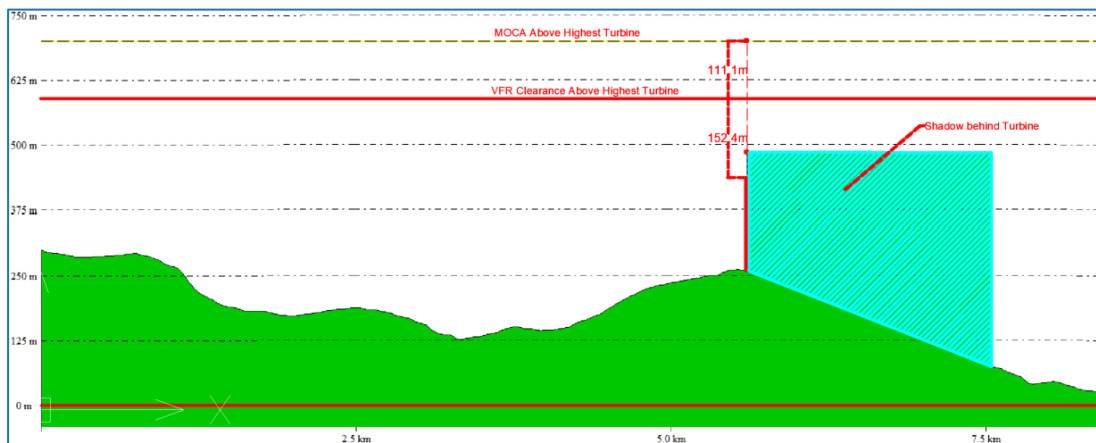


Figure 15: Radar Line of Sight with wind farms shown in blue together with minimum radar surveillance coverage at 2,300ft is maintained.

## 5.7. Horizontal Coverage

5.7.1. To determine the horizontal shadow areas, lines of the dimensions modelled are shown in Figure 16 and overlaid onto a Google Earth™ image shown in Figure 16. The shadow areas are very thin being only 46m wide. Consequently, the probability of loss of SSR returns over the wind farm is minimal. Eurocontrol defines a 'Loss' as being failure to detect two or more target positions. This definition is used by most ANSP's in their Surveillance System Safety Cases. The crossing direction of the aircraft also impacts this probability. Therefore, with the probability of an aircraft position being exactly on two consecutive shadow areas is very unlikely to occur. From this it could be concluded that any potential Operational impact to ATC should be acceptable.

- 5.7.2. Importantly, there is no impact on the long-range coverage as required for the provision of the En-Route Air Traffic Service.



Figure 16: Knockshanvo Wind turbine positions

## 5.8. Cumulative assessment of the shadowing

- 5.8.1. Figure 17 Shows the position of the proposed turbines for Oatfield windfarm along with those for Knockshanvo windfarm. The cumulative effect of the shadows from the combined windfarms are still likely to have minimal operational impact.
- 5.8.2. A common concern is the ‘cumulative effect’ whereby individual wind farm developments would not be a problem for Air Traffic Service providers, but together they have an impact. The nearest development to Knockshanvo Wind Farm is Oatfield Wind Farm. Applying the same methodology for this development results in the surveillance coverage shown in Figure 18. The areas of poor detection are shown as red lines of 2Km length and just 30m wide.



Figure 17: Combined turbines for Knockshanvo and Oatfield windfarms

5.8.3. As can be seen from Figure 17, the cumulative impact from Knockshanvo windfarm and Oatfield windfarm on SSR coverage is minimal, with considerable horizontal coverage in the vicinity of both wind farms and within them.



Figure 18: Woodcock Hill MSSR Shadow areas by the Knockshanvo Turbines

5.8.4. Figure 18 shows the combined wind farm shadow area in relation to Shannon Airport. As shown in Figure 16 the vertical extent is very limited being < 60m above the highest turbine blade tip.

## 6. TNO

### 6.1. Independent Report

6.1.1. The applicant commissioned a report from TNO, published in January 2026, titled: "Detailed Engineering Assessment for the Secondary Radar at Woodcock Hill". A Detailed Engineering Assessment (DEA) is called for in the Eurocontrol guidelines to assess the potential impact of wind turbines on SSR when the wind turbines are located closer than 16km. As the closest turbine proposed for Knockshanvo will be approximately 5.6km this TNO study is appropriate.

6.1.2. The TNO report concludes that modelled errors due to these wind turbines could have an effect on the MSSR performance due to the newly planned wind turbines when the target is in a specific area. It is important to note that these errors are the worst-case scenario of Woodcock Hill MSSR processing an erroneous signal into a single plot. The probability remains extremely low that this small error potential will result in a false track which is confirmed within the TNO report also when their report refers to the "smoothing" function of the MSSR.

6.1.3. AirNav claim that :

*"This development would compromise the Woodcock Hill radar's compliance with EU mandated surveillance performance criteria required to support 5 Nautical Mile horizontal separation of aircraft in En-Route Irish airspace and 3 Nautical Mile horizontal separation of aircraft in Dublin airspace".*

6.1.4. The TNO Report Supports Cyrrus as it shows that the potential impacts from the Knockshanvo wind turbines does not occur over Dublin Airspace but to the North East of the country.

6.1.5. The TNO report also indicates that another existing MSSR (i.e., MSSR Tooman) provides overlapping coverage with Woodcock Hill MSSR thereby ensuring redundancy within the ARTAS multi-radar tracker system and maintaining surveillance performance. This is in line with the Cyrrus view that the network of MSSRs across Ireland provides redundancy in the air coverage and using the ARTAS system. There is no expected reduction in surveillance performance required to support both the 5NM horizontal separation of aircraft in En-Route Irish Airspace and 3NM horizontal separation of aircraft in Dublin Airspace arising from the Knockshanvo Windfarm.

## 7. Conclusion

### 7.1. Recommendations

- 7.1.1. Timescales for the upgrade of the Shannon Airport PSR with co-mounted SSR should be provided by AirNav to clarify if an interim upgrade is required to the STAR2000.
- 7.1.2. Timescales for the planned upgrades to the Woodcock Hill radar system should be provided by AirNav to clarify if an interim upgrade is required to the RSM970.
- 7.1.3. As the manufacturer and Design Authority, AirNav request that Thales assess the type of mitigation package required (if any). They will confirm costs and timescales based on their scope of work.

### 7.2. Summary

- 7.2.1. As shown in the TNO report, there is a negligible impact on the MSSR performance Woodcock Hill radar. Consequently, AirNav should be able to confirm there is no Operational Impact. The performance of the MSSR system at Woodcock Hill will not be unacceptably impacted by the proposed 9-turbines at Knockshanvo. The MSSR at Woodcock Hill has inbuilt capabilities to filter wind turbine impacts.
- 7.2.2. The PSR at Shannon Airport may already be capable of filtering the wind turbines. Furthermore, Thales can provide various upgrades to further reduce the impact. These mitigations would result in the proposed 9-turbine windfarm at Knockshanvo having no operational effect. Any upgrade to the existing PSR may be unnecessary depending on timescales for the already contracted upgrade by Thales to the STAR NG.



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## Appendix D - TNO Capability Statement

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Date  
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Our reference  
100360052  
Project number  
060.67849

Subject    Engineering assessment capabilities of TNO  
              regarding effects of wind farms on radar systems

Dear Mr. Hayes,

The following is a statement of TNO's capabilities on simulating and reporting the effects of wind turbines (or other tall buildings\structures) on radar systems.

**About TNO in general:**

TNO (<https://www.tno.nl/en/>) is an independent research organization in the Netherlands founded in 1932. We connect people and knowledge to create innovations that boost the sustainable competitive strength of industry and well-being of society. For this purpose, TNO is established by law as legal public entity. The TNO-law gives us a number of special tasks and frameworks and linking it to specific conditions under which we have to perform our work. So that we can continue to create independent and reliable solutions to the challenges that society presents us.

**About Radar research at TNO:**

TNO has been one of the pioneers in the world in the development of Radar systems. Already before World War II we started developing the first Radars. Today the Radar Technology department, of around 60 mostly academic researchers, is still leading on several topics like: (phased) array antennas, RF-electronics and Radar signal processing. Our role can differ from: early scientific outlook on future technology via development of the next generation Radar systems via testing Radar systems to be installed to technical consultancy on and assessment of operational Radars.

The General Terms and Conditions for commissions to TNO, as filed with the Registry of the District Court in the Hague and with the Chamber of Commerce and Industry in The Hague, shall apply to all commissions to TNO. Our General Terms and Conditions are also available on our website [www.tno.nl](http://www.tno.nl). A copy will be sent upon request."

**About our assessments of the effects of wind farms on the Radar coverage:**

Within the Radar Technology department we also simulate the probability of detection and coverage of operational military and civil Radar systems using the software tools CARPET™ and PERSEUS™ both developed by TNO. The latter, PERSEUS™, has been specifically designed to assess the effects of wind turbines on the coverage of Primary Surveillance Radars (PSR), which detect non-cooperative targets, which is mandatory for our MoD. More information can be found on the website:

<https://www.tno.nl/en/safe/integrated-air-missile-defence/perseus-wind-turbine-radar-interference/>

We have a track record of over 30 years starting in the Netherlands but from 2015 also for wind farm developers in several other countries amongst which are Belgium, Denmark, United Kingdom and now Ireland. Apart from wind farm developers we also support Air Navigation Service Providers (ANSP's). For instance, we recently performed a study for Skeyes, the Belgium ANSP to determine the impact of large wind turbines on their primary and secondary radar. Based on these results the Belgium Ministry of Defense and Skeyes adapted their regulation, by reducing the no-go zone for smaller wind turbines and increase the DEA requirements for wind turbines with a tip heights of more than 230 m. TNO is also capable of assessing the effects of wind farms on the Monopulse Secondary Surveillance Radar (MSSR), for cooperative aircraft with a transponder and on TACAN (military Tactical Air Navigation beacon) systems. For the MSSR a line-of-sight analysis and coverage maps are generated and the off-boresight error (OBE), so the error in the detection angle of the Radar with respect to the actual target position, is calculated.

As an independent organisation we use the input from the wind farm developer (*wind turbine brand/model and locations together with a height map of the country*) and the information on the Radar system(s) to simulate the effects. The outcome is a report, which can be used by an ANSP or the MoD (Ministry of Defense, typically the Air Force) to decide if the effects of the planned wind farm are acceptable.

Sincerely,

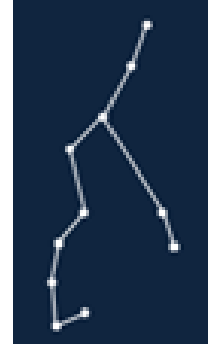
Valid Signed by Duije Deurloo  
on 2026-01-15 11:51:08

D. Deurloo  
Radar design and consultancy

Appendix E - TNO Perseus Overview

# Program for the Evaluation of Radar Systems in an Extended Urban Setting

# PERSEUS



TNO 2024 – March 2024

## PERSEUS

### Program for the Evaluation of Radar Systems in an Extended Urban Setting

Author(s)	Onno van Gent Arne Theil
Classification report	TNO Public
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# 1 Introduction

Since 1996, radar performance degradation due to wind turbines has been part of the research portfolio of TNO. Several radar studies have been performed for the Netherlands Government. In 2009 TNO has been contracted by the Dutch government to develop a high fidelity simulation tool, PERSEUS, to assess the wind turbine interference on Dutch primary surveillance radars (PSRs). Currently, TNO is the only organisation within The Netherlands authorised by the Ministry of Defence to perform the radar impact assessment for their radars, being five Raytheon ASR-10SS PSRs, the Selex ATCR-33K radar at Schiphol airport (TAR4) and two military long range 3D radars. See Figure 1.1.



Figure 1.1: Antennas of the Raytheon ASR-10SS (left), MPR 3D radar (middle) and the Selex ATCR-33K or TAR4 (right).

Apart from these radars TNO also has additional radar models for other modern radars such as the Raytheon ASR-23SS, Thales STAR 2000, SMART-L EWC GB and SMART-S Mk2, Hensholdt ASR-NG, Hensholdt ASR-S and Terma Scanter 4002. See Figure 1.2. TNO has good relationships with the radar manufacturers involved (Raytheon, Selex, Thales, Hensoldt and Terma).



Figure 1.2: Antennas of the Raytheon ASR-23SS (top-left), Thales STAR 2000 (top-middle), Hensoldt ASR-NG (top right), Thales SMART-S Mk2 (bottom-left) and the SMART-L EWC (bottom-middle) and Terma Scanter 4002 (bottom-right).

The radar model used in PERSEUS is based on the renowned CARPET Radar Performance Analyses tool of which over 600 licences have been sold worldwide. The model is constantly updated to accommodate enhanced signal processing within modern radars.

Currently, TNO is performing a study for the Ministry of Defence, the Ministry Infrastructure and Environment and Ministry of Economic Affairs on the impact caused by different 6000+ MW wind farm scenarios. These scenarios consist of more than 3000 on-shore and off-shore wind turbines all having different dimensions and peak-powers.

During the years of performing radar interference assessment TNO has gathered a large amount of 3D CAD models of wind turbines from all major wind turbine manufacturers such as Enercon, Goldwind, Lagerwey, Nordex, Senvion, Siemens-Gamesa and Vestas which can be applied within PERSEUS.

In Chapter 2 of this document the assessment tool for the primary radar is described, in Chapter 3 tooling for secondary radar is discussed. Examples of results are given in these sections. Chapter 4 presents an overview of radar parameters that PERSEUS needs to know.

## 2 Primary radar assessment tooling

### 2.1 PERSEUS and detailed assessment from Eurocontrol Guidelines

The robustness of a primary radar system against wind turbines highly depends on the radar architecture. Details matter, and TNO therefore utilizes high fidelity models of the radars involved. Among the modelling aspects are the detection algorithm (CFAR processing), beam combining on receive (if applied), Doppler processing, and the radar waveform, i.e., pulse shapes including pulse compression, frequencies and instantaneous bandwidths. An overview of radar parameters that PERSEUS uses is given in Chapter 4.

It is also acknowledged that the backscatter from wind turbines is highly variable, and dependent on parameters such as wind direction and pitch angle of the wind turbine blades. Similarly to modelling the backscatter from a target, PERSEUS uses a representative model for wind turbine backscatter, which has been derived from ‘live’ radar measurements of wind turbine backscatter. Within PERSEUS no discrimination is made between the EUROCONTROL’s Simple Engineering Assessment (SEA), more than 15 km distance of the wind turbine to the radar, and the Detailed Engineering Assessment (DEA), less than 15 km distance of the wind turbine to the radar. The effects are calculated over the full instrumented range of the radar.

### 2.2 Terrain elevation database

Within the Netherlands, PERSEUS uses a terrain elevation database with a spatial resolution of 10 m called AHN2, which has been collected by the Netherlands authorities. It contains highly accurate information on the altitude of the ground level and building altitudes. Outside the Netherlands, TNO uses often Shuttle Radar Topography Mission (SRTM1) elevation data. This database provides ground level height information with a resolution of 1 arc second (30 m along a meridian, approximately 15 m along a line of constant latitude in the Benelux countries). If required, TNO can insert a better resolution elevation database for specific areas, or countries. For the propagation PERSEUS utilises the well-known TERPEM propagation engine from Signal Science Ltd (see <http://www.signalscience.com>). This propagation engine models refraction as well as multi-path effects. TERPEM results are presented in Figure 2.1.

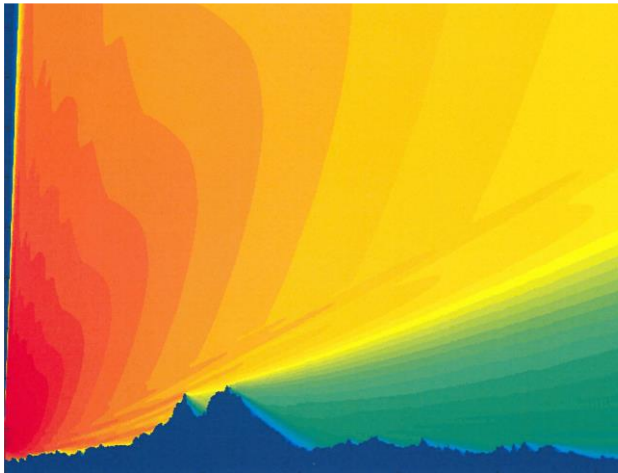


Figure 2.1: Typical example of the diffraction calculated by TERPEM.

## 2.3 PERSEUS versus RASCAL

TNO has performed a number of radar performance calculations for LVNL, the civil air navigation service provider (ANSP) of The Netherlands. LVNL has compared the PERSEUS results with the results obtained with the RASCAL tool from Eurocontrol. Note that the RASCAL tool is an optical line of sight tool only, i.e., it does not model the actual detection capability of the radar. Figure 1 shows results of both models. The data from RASCAL has been obtained from theodolite measurement at the position of the radar antenna. For this example PERSEUS used the earlier mentioned high resolution AHN-2 altitude database. Note that the colour axis in the PERSEUS result (right image) indicates single scan detection probability.

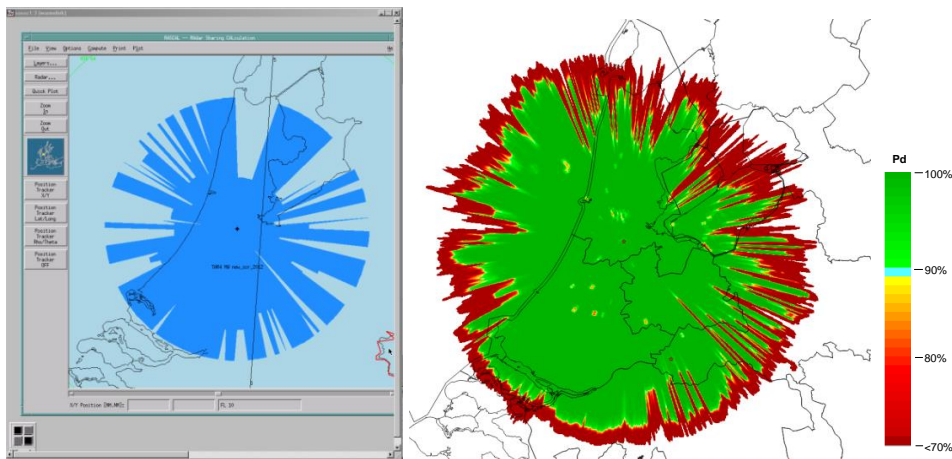


Figure 2.2: Comparison between RASCAL (left) and PERSEUS (right), both calculated for a target at 1000 ft. altitude.

Clearly, the TNO output is more detailed. There are, however, also certain similarities.

## 2.4 Detailed radar processing modelling

An example of the effects of the detail modelling is provided in this section. CFAR (Constant False Alarm Ratio) processing avoids radar from processing too many false detections. Typically a threshold is set for every individual range cell. If a target echo exceeds the

threshold, detection is made. The level of the threshold is determined by averaging the measured level of a number of range cell in front (leading window) and behind (trailing window) of the cell under test (CUT). This is illustrated in Figure 2.3. This process can be corrupted due to strong Doppler reflections or flashes from the rotating blades of wind turbines. As shown in Figure 2.4, if a Doppler reflection appears in the CFAR leading or trailing window, the threshold is raised at the cell under test and consequently the target echo within the cell is lost.

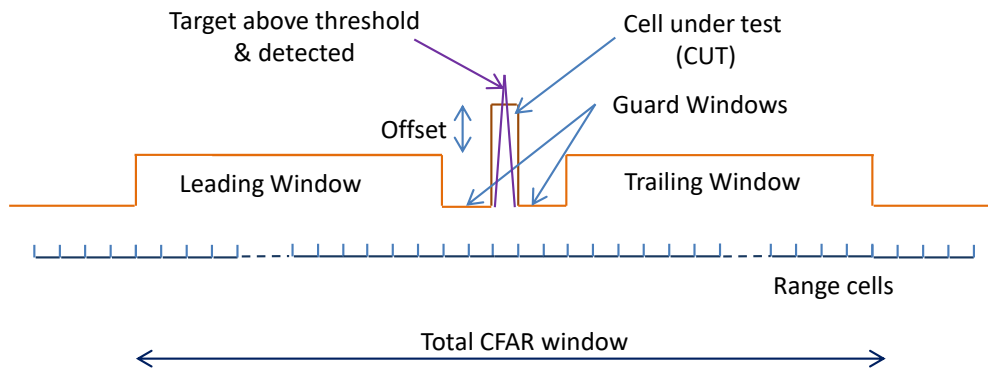


Figure 2.3: The typical operation of the CFAR processing

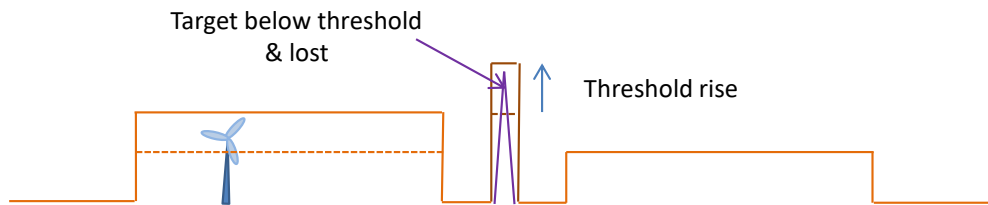


Figure 2.4: If a Doppler reflection appear in the CFAR leading or trailing window the threshold is raised at the cell under test and consequently the target echo within the cell is lost.

Detection loss may occur over the full range of the CFAR window. The effect on the detection probability is shown in Figure 2.5. This figure also shows the effects if the CFAR processing is improved and in case parallel processing is applied for both the low and high beam. Hence high-fidelity radar processing simulations are mandatory to assess wind turbine interference on radars.

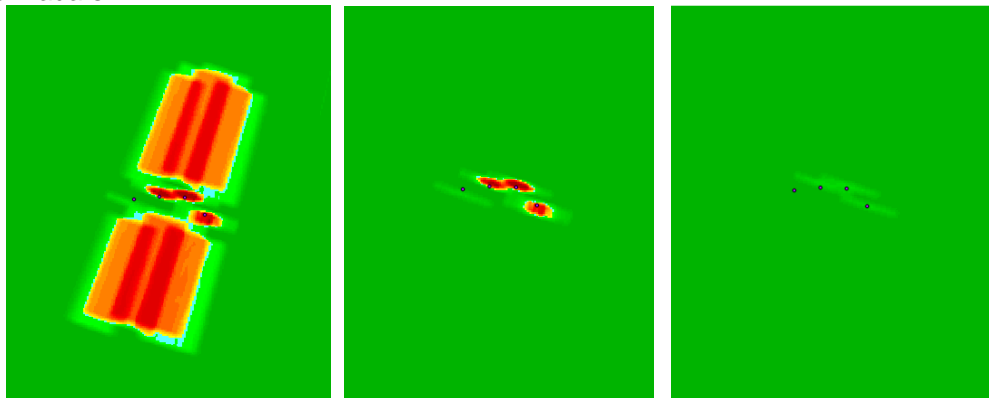


Figure 2.5: An example how a wind turbine Doppler reflection potentially can cause loss of detection probability over a large area in front and behind a wind turbines for a target flying at 1000 feet. The turbine positions are indicated by purple dots. In the middle the results if an improved CFAR process is used. The

loss of detection is now limited to the range cell that coincide with the wind turbine position. On the right in case parallel processing is applied for both the low and high beam for target flying at 4000 ft.

Another example is the performance improvement that can be realised when introducing a high resolution infill radar to a typical air traffic control radar to mitigate the effects of wind turbines on the primary radar picture, see Figure 2.6.

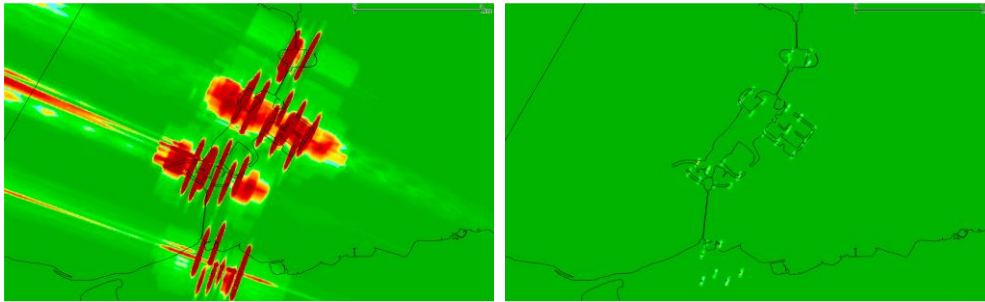


Figure 2.6: An example of the performance improvement that can be realised when introducing an high resolution infill radar (right) to a typical air traffic control radar (left). The turbine positions are indicated by purple dots.

## 2.5 Results from PERSEUS

Figure 2.5 to Figure 2.10 show output of a number of PERSEUS calculations. Please note that the PERSEUS output can be provided in GeoTiff format, which makes it easy to combine within any GIS tool, such as QGIS or ArcGIS.

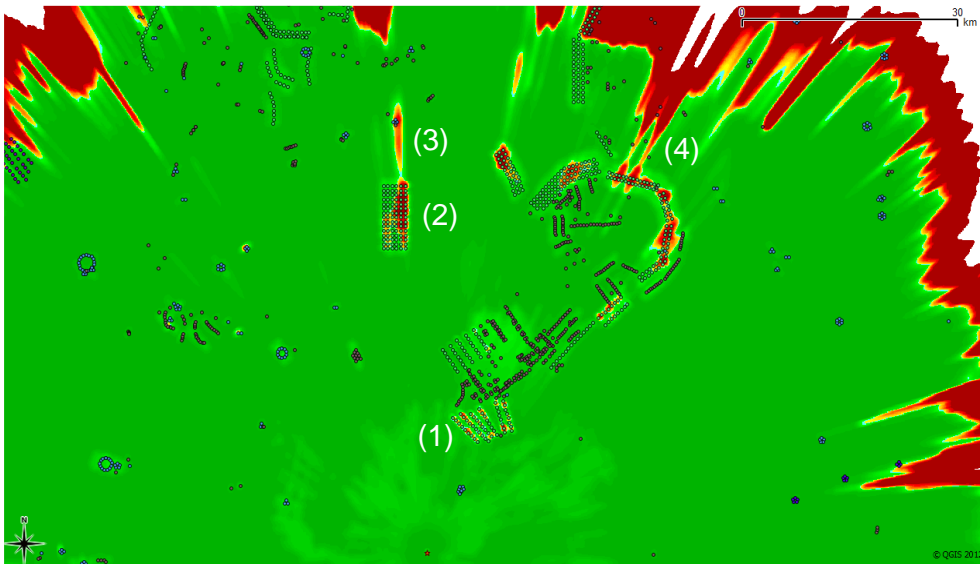


Figure 2.7: Example of a calculated coverage diagram of a radar and a high number of interfering wind turbines. The location of the radar is indicated by the star at the bottom-left of the picture. Differently sized turbines are shown as dots, with different colours. The diagram shows a variety of effects, such as desentisation overhead due to the CFAR (1), cumulative shadows (2), time side lobes due to pulse compression (3) and loss of maximum coverage due to shadows of wind turbines (4).

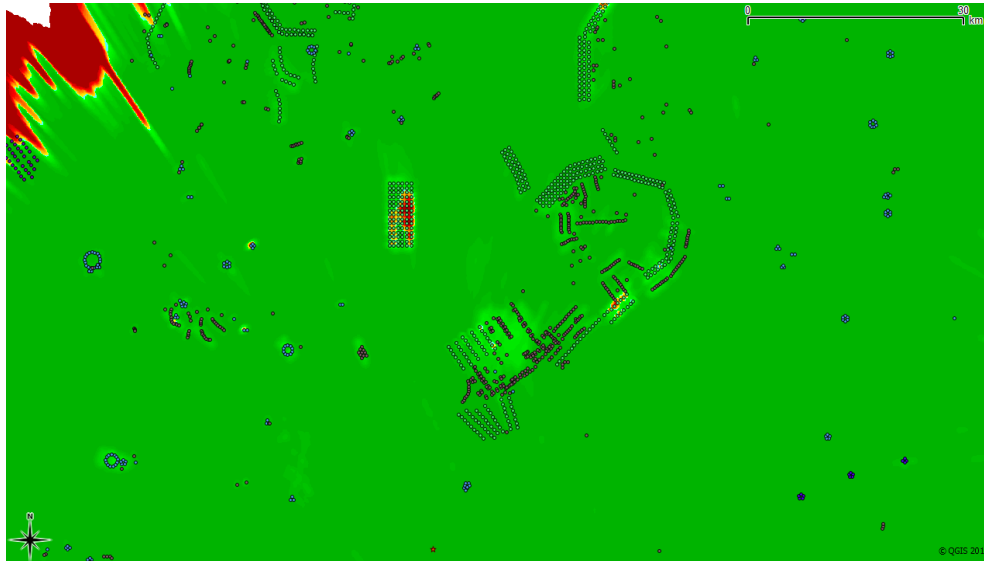


Figure 2.8: The same situation as shown in the previous figure. In this case however, a combined detection probability diagram is shown; three PSRs contributing to the fused radar picture.

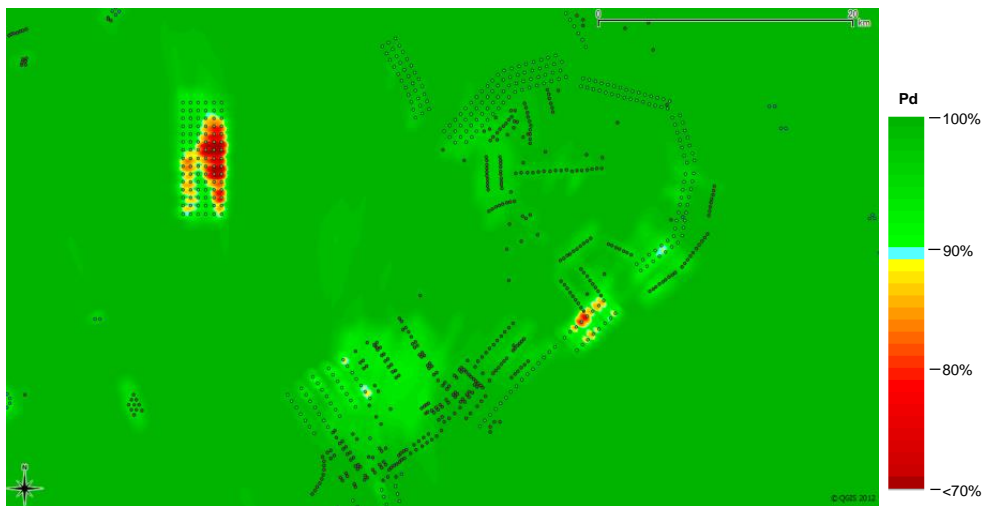


Figure 2.9: Same as shown in Figure 2.8 but now zoomed in towards a number of individual wind turbines. Right: the colour legend that has been applied.

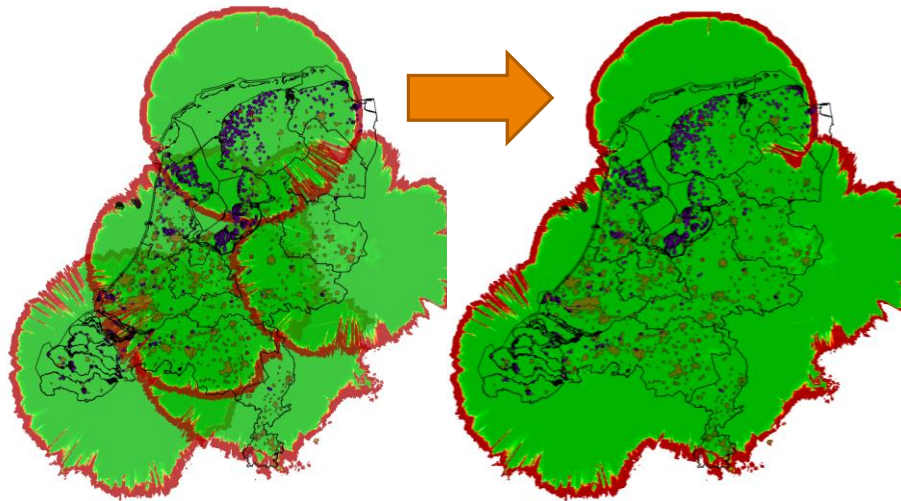


Figure 2.10: The radar detection coverage at 1000 feet of five individual radars are fused into a single coverage diagram.

Figure 2.11 shows the type of improvement that can be realised above a wind farm consisting of 96 wind turbines by added an extra radar and fuse the radar data to a common picture.

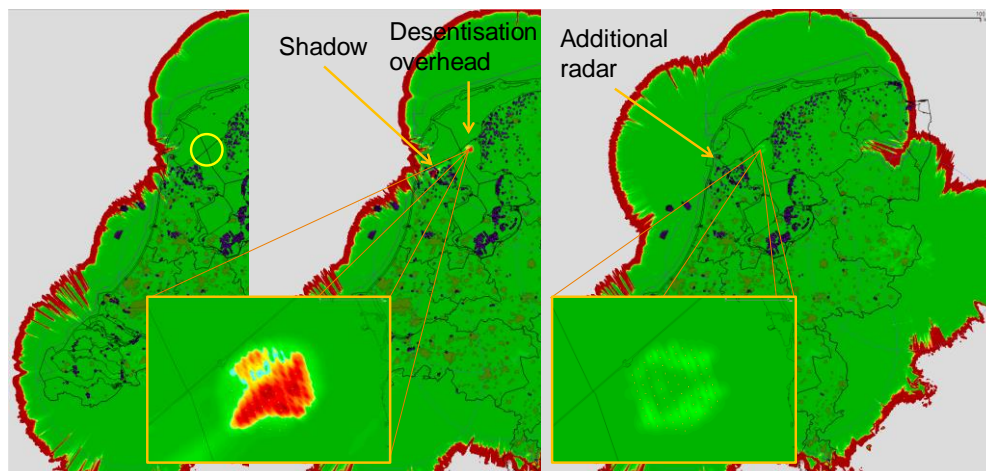


Figure 2.11: The improved performance at 1000 feet above a wind farm consisting of 96 wind turbines by adding an extra radar to the fused radar picture.

# 3 Secondary radar assessment tooling

## 3.1 Introduction

The presence of wind turbines can influence the performance of MSSRs. In order to correctly interpret the results of the line-of-sight analysis, we address the most important issue that can arise whenever a wind farm is near a secondary radar system: bearing errors. SSRs differ from PSRs in a number of ways. PSRs do not depend on cooperation of aircraft, they merely measure range, bearing and sometimes also elevation angle and radial velocity. SSRs demand that aircraft cooperate, *i.e.*, the aircraft actively participates in its detection. The SSR sends out an interrogation signal at 1030 MHz. The target, carrying a radar transponder, subsequently replies by transmitting a response signal at 1090 MHz. This response contains additional information regarding the target, *e.g.*, barometric altitude (mode C) and an identity code (mode A). In the case of monopulse SSR (MSSR), the system is capable of making a precise bearing estimate of the target from a single reply signal (hence, monopulse). The bearing estimate is generally accurate within a fraction of a degree ( $\sim 0.05^\circ$ ). The presence however of an obstacle (like a mountain, building or wind turbine) between the MSSR antenna and the target can cause an error in the estimation of the bearing to the target.

In Figure 3.1 an MSSR antenna is shown, typically comprising 35 antenna elements. Below we first give a short description on how the bearing measurement is carried out and how the wind turbine influences this measurement.



Figure 3.1 The secondary radar antenna, comprising of 35 antenna elements, on top of a STAR 2000 antenna.

The bearing to a target is determined using the so-called monopulse technique. By applying different weight factors for each antenna element, two radar beams are created with the same antenna, the so-called *sum beam* and *difference beam*, see Figure 3.2. A reply is received by both beams. By comparing the signal strength in the sum beam to the signal strength in the difference beam an accurate bearing angle can be estimated. Left-right ambiguity is solved by looking at the phase of the signal. For example, when the sum and difference beam record a pulse with the same signal strength, looking at Figure 3.2 we see that the bearing to the target must be, depending on the phase, either  $+1^\circ$  or  $-1^\circ$ .

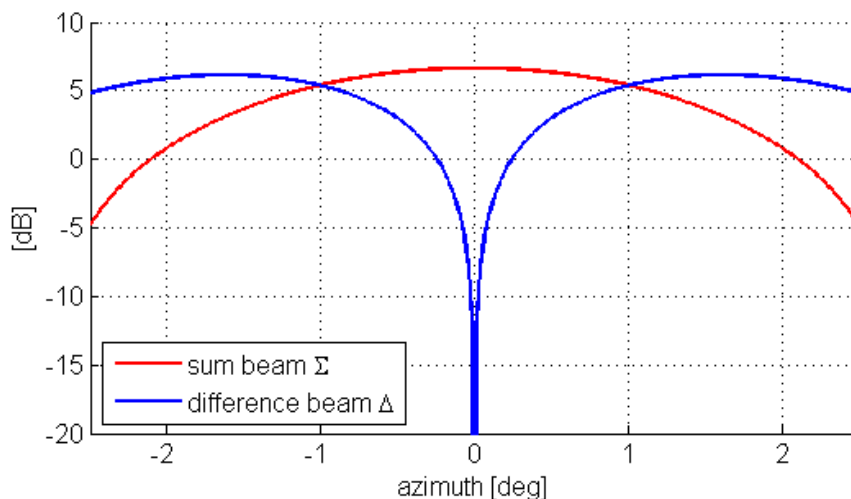


Figure 3.2 The sum beam (red) and difference beam (blue) used within the TNO model. The bearing of the target is estimated by comparing the signal strength of a single reply signal in both beams.

If a wind turbine is positioned between the target and the radar, the electric field is distorted both in phase and amplitude. This is illustrated in Figure 3.3. The distorted field effectively

changes the weight factor at each antenna element, thus, changing the shape of the sum beam and difference beam. As the two beams are influenced differently by the wind turbine, so is the signal strength measured in both beams. Therefore, when the signal strength is compared to estimate the bearing, an error is introduced.

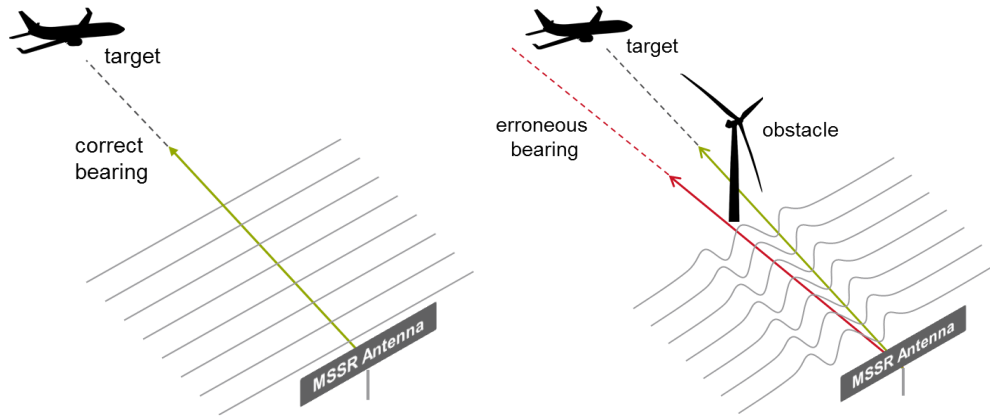


Figure 3.3 A wind turbines, positioned between target and MSSR antenna can disturb the transponder signal, introducing an error in the bearing estimate.

The bearing error as a function of azimuth has been calculated. This will give us insight in the width of the zone in which the MSSR is influenced by the wind turbine. To estimate the bearing error we use an analytical solution for an incident plane wave on a cylinder with fixed radius and infinite length. The method calculates the phase and amplitude of the perturbed wave front on each antenna element. From this the bearing error is determined. The method is described in full in [11]. In this reference the method has been validated using real data of an MSSR partially obstructed by a metal mast of width ~2 m at a range of approximately 600 m.

TNO has conducted its own validation of the method as well using real MSSR data. In this validation the MSSR is partly obstructed by an ATC tower with a maximum width of 20 m at a range of approximately 2 km. In both cases, the calculated bearing error as a function of azimuth matched relatively well with the measured data. Figure 3.4 shows the close match between real recorded MSSR track of an aircraft at a distance around 175 km from the MSSR and the simulated data. Secondary effects at coordinates [4, 178] and [-4, 174] km appear accurately modelled as well (indicated by red arrows).

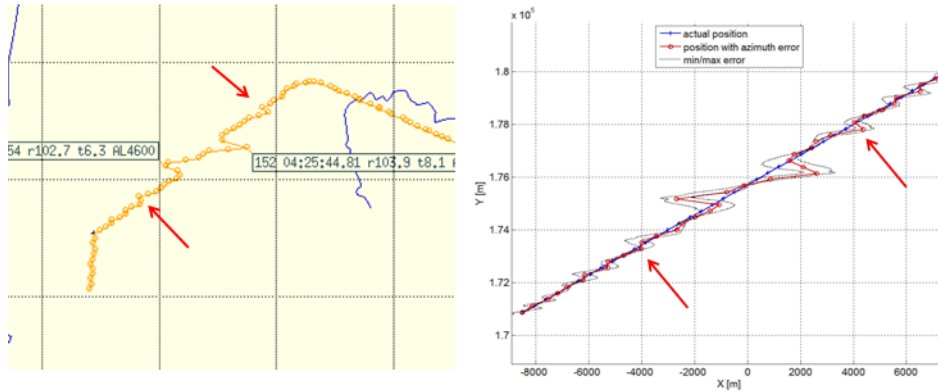


Figure 3.4: Comparison of a MSSR track recoding of a real aircraft and the simulated results. Secondary effects at coordinates [4, 178] and [-4, 174] km appear accurately modelled as well (indicated by red arrows).

As mentioned, the method uses a cylinder of infinite length to model the obstacle. An infinite cylinder can be described by just a single parameter, the width. In our simulations we have chosen the width of the cylinder to be dependent on whether or not the nacelle or blades can be seen by the radar. (1) In the orange areas, the width of the cylinder is equal to the average of the width and length of the nacelle. (2) In the red areas, the width of the cylinder for all visible wind turbines is set to the width of the blade. See Figure 3.5.

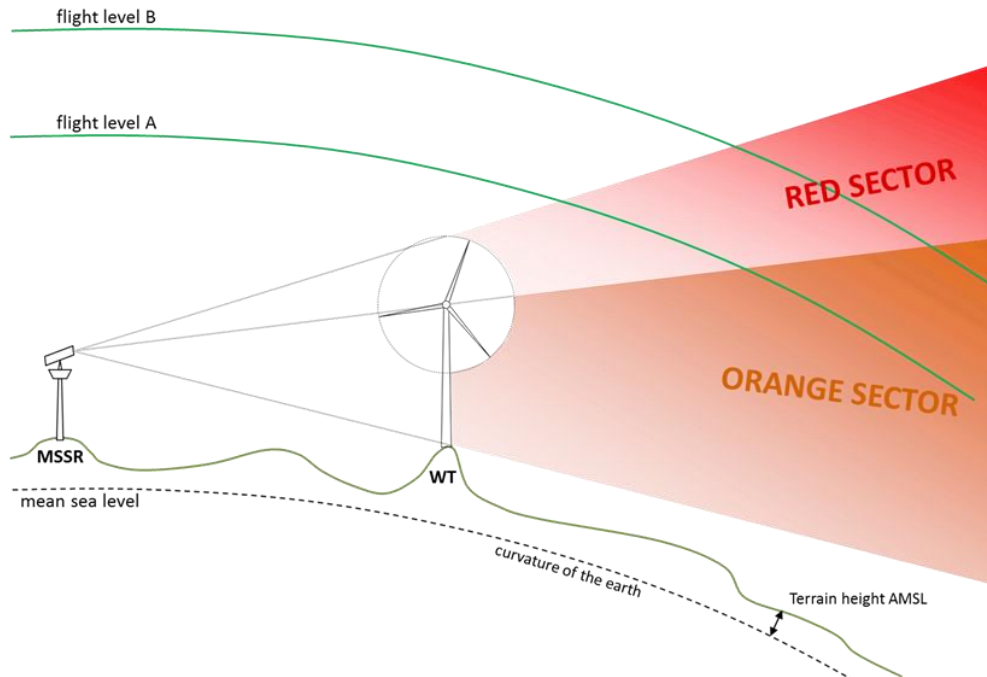


Figure 3.5 The orange and red areas, shown in the LoS coverage diagrams are in fact cuts through a volume behind the wind turbines. The calculated OBE is thus valid at all flight levels shown in the LoS coverage diagrams.

It is assumed that there is always a wind turbine blade with a vertical orientation. The full tip height of the turbine is used in the analysis. As there is not always a wind blade directed vertically, this is a worst case assumption.

Furthermore, the applied method describes the incoming signal as a plane wave (as depicted in the left image of Figure 3.3). The approximation of the incoming radiation as a plane wave is valid in case the distance between the target and the obstacle is sufficiently large. To see if the plane wave approximation is valid, we calculate at which distance the phase difference between the two ends of the wind turbine blade is equal to half a wavelength. The path difference  $\Delta r$  from one end of the blade to the other can be approximated by  $\Delta r = L^2/2R$ , where  $L$  is the length of the blade and  $R$  is the range. Setting  $\Delta r$  equal to half a wavelength,  $\lambda/2$ , and filling in  $L=60.7$  m, we find  $R = 13$  km at 1090 MHz. We see that the incoming wave for a target at 13 km behind the obstacle already resembles a plane wave quite closely. For targets at larger distance the resemblance will be even better. For targets closer than 13 km to behind the wind turbine, the estimated bearing error is a first order approximation.

Regarding the geometry of the situation, we take into account two parameters: (1) the azimuth angle to the target, relative to the obstacle and (2) the orientation of the radar antenna at the moment the reply is received. Given a wind turbine at a certain azimuth,  $\alpha$ , we let the target move from  $\alpha - 4^\circ$  to  $\alpha + 4^\circ$  in 501 steps. At more than  $4^\circ$  azimuth from the wind turbine the error reduces rapidly to values much smaller than the accuracy of the MSSR (typically  $0.05^\circ$ ). For each position of the target, the radar antenna is rotated over  $3^\circ$ , from  $-1.5^\circ$  to  $1.5^\circ$ , where  $0^\circ$  corresponds to the antenna looking directly at the target. For each geometry the disturbed electric field is calculated. This is done for each (visible) wind turbine in the wind farm separately. Subsequently, all disturbed fields are summed and the bearing error for the total field is calculated.

A typical example of the off-boresight error for a single obstacle (cylinder width 25 m) at a range of 3 km is shown in Figure 3.6. The obstacle is located at an azimuth angle of  $218.5^\circ$ . The red, orange and grey lines represent the 50<sup>th</sup>, 90<sup>th</sup> and 100<sup>th</sup> percentiles, respectively. This means that at a given azimuth angle, the error is in 100% of the cases contained within the two grey lines, in 90% of the cases between the two orange lines. The error at a given azimuth angle is thus not a single number, but lies in the range defined by the two grey lines. The reason this happens, is that, as mentioned above, the geometry between the rotating antenna, target and obstacle can differ for a target at a given azimuth. The grey line thus gives the upper limit of the bearing error to be expected at a given azimuth angle. This is the case when the radar antenna is in the least favourable orientation when receiving the reply signal.

As can be seen in the figure below the off-boresight error caused by a single obstacle is point symmetrical around the azimuth to the obstacle. Directly behind the obstacle, the error is zero. In this case the sum and difference beams are equally disturbed, resulting in no error. Note that in the case of multiple obstacles at different ranges, the symmetry is broken.

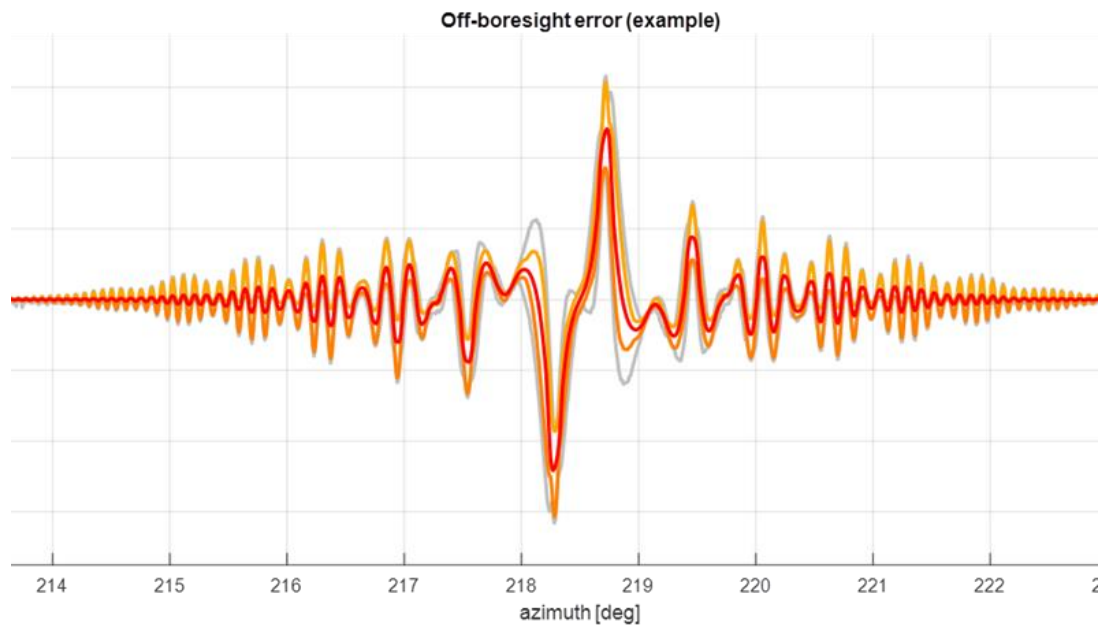


Figure 3.6 The off-boresight error for an infinite cylinder with a width of 25 m at a range of 3 km from the radar antenna. The error is point symmetrical around the azimuth angle to the obstacle.

## 3.2 Line of sight

This analysis will give insight into the visibility of the wind farm as seen from the MSSR position.

The analysis takes into account both the curvature of the earth as well as the shape of the terrain. Radio waves do not follow straight lines, but tend to curve along the surface of the earth to some extent as the refractivity index of the air varies with altitude. These refraction effects are generally taken into account by multiplying the radius of the earth by a so-called  $k$ -factor. A common value for the  $k$ -factor is 1.33, which has been used in all results. By using the  $k$ -factor, we can treat the radio waves as if travelling along straight lines instead of curved lines.

In order to do the line-of-sight analysis, a digital elevation model (DEM) is required. We use the same DEM as used for the primary radar Detailed Engineering Assessment described earlier in this report. As mentioned earlier, the terrain altitude data in the DEM is taken from the Shuttle Radar Topography Mission (SRTM) database.

We show the extent of the wind farm in azimuth and elevation for the MSSR. These results reveal if the wind farm has impact on the radar horizon. A wind turbine influences the radar horizon when the elevation angle to the tip height of the wind turbine is larger than the elevation angle to all other objects at the same azimuth angle, extending all the way up to the instrumented range of the secondary surveillance radar (assumed to be up to 256 NM). Given the elevation angle to the tip height, aircraft at different altitudes are influenced at different ranges as shown in Figure 3.7 below.

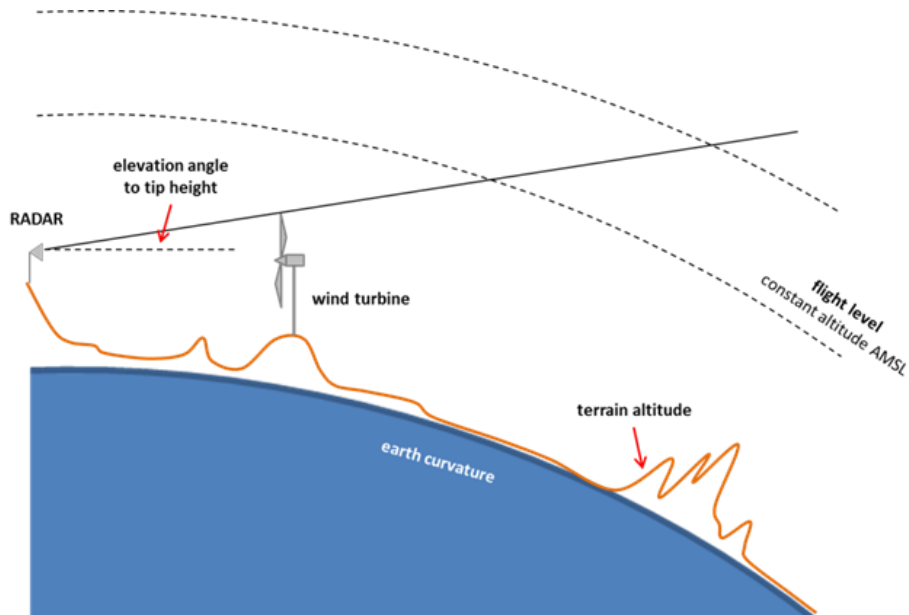


Figure 3.7 Overview of the overall line-of-sight geometry at fixed azimuth. The elevation angle to the tip height of the wind turbine is indicated by a grey line. MSSR replies of aircraft above this line are not affected by the wind turbine. Aircraft replies below the line may be influenced by the wind turbine.

An example of the typical line of sight overview for an individual wind turbine is shown in Figure 3.8. The red line in each figure represents 0 m AMSL. The black line above the red line shows the terrain altitude along the azimuth line towards the wind turbine. The radar is indicated by a red triangle on the left of each figure. The wind turbine is drawn at its particular range in each figure. The first Fresnel zone towards the tip and hub heights of the wind turbine are drawn as dashed red and blue ellipsoids respectively. The wind turbine is only invisible by the MSSR incase both zones are fully blocked.

A dashed black line passes through the point on the ground with the largest elevation angle as seen from the radar antenna. This is the point that determines the radar horizon in absence of the wind turbine. Furthermore, a red and orange zone are drawn. When orange and red zones are visible, the radar horizon is diminished by the wind turbine. The red zone indicates the reduction of the radar horizon due to the blades of the wind turbine.

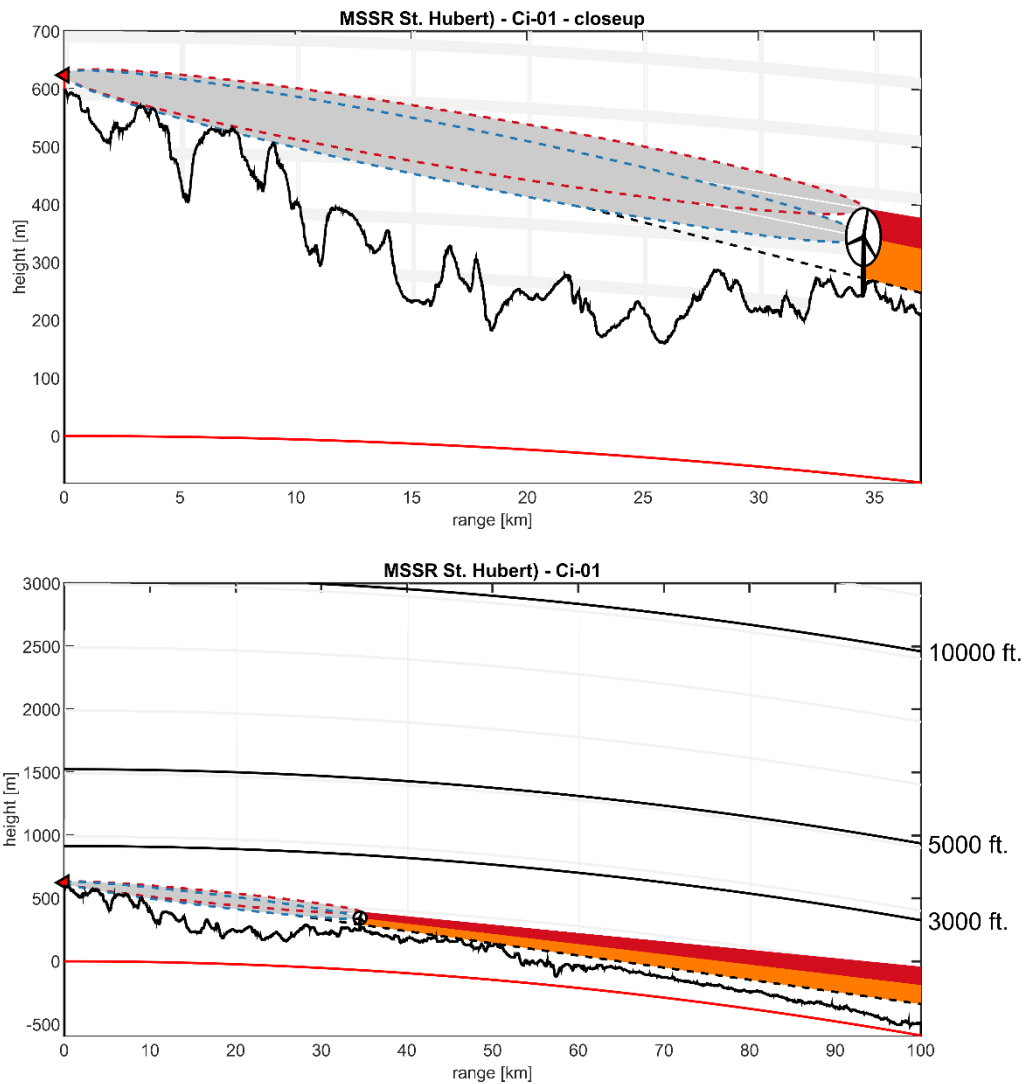


Figure 3.8 Line-of-sight towards a turbine as seen from the MSSR. The radar has line-of-sight towards the wind turbine. At the top a close-up picture and at the bottom the situation up to 100 km.

In Figure 3.9 we show azimuth-elevation plots of the surrounding terrain (the radar horizon) including the wind farm. The horizontal red lines indicate the blades of the wind turbine at hub height. Note that the scaling of the horizontal and vertical axes in these figures is different. This means that the wind turbines appear high and narrow. The width of the blades in the horizontal direction (azimuth) is in fact the actual width of the wind turbine as seen from the radar.

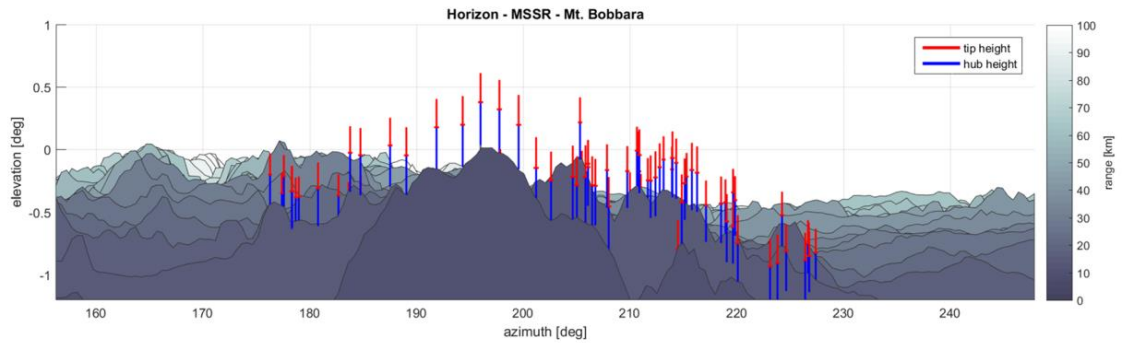


Figure 3.9 A wind farm, including the terrain profile, showing the individual wind turbine location, as seen by the MSSR.

We can also show the locations of the affected areas in a horizontal line-of-sight coverage diagrams. Coverage diagrams may be shown for targets at altitudes of 3000, 5000 and 10000 ft for the existing situation and after the newly planned wind turbines has been build. A coverage diagram shows whether the performance of the secondary radar can be influenced by the target at a given altitude.

For each target height two cases are considered: the coverage when there are no turbines present and the coverage for the case the planned turbines are considered. By comparing these figures the effects of the planned turbines on the line-of-sight coverage can be determined.

The line-of-sight coverage diagrams for the MSSR at target heights of 3000 ft, 5000 ft and 10000 ft are shown in Figure 3.10 up to Figure 3.12. Areas affected by the mast up to the hub height of the wind turbines are shown in orange. Areas affected from hub height up to the tip height are shown in red.

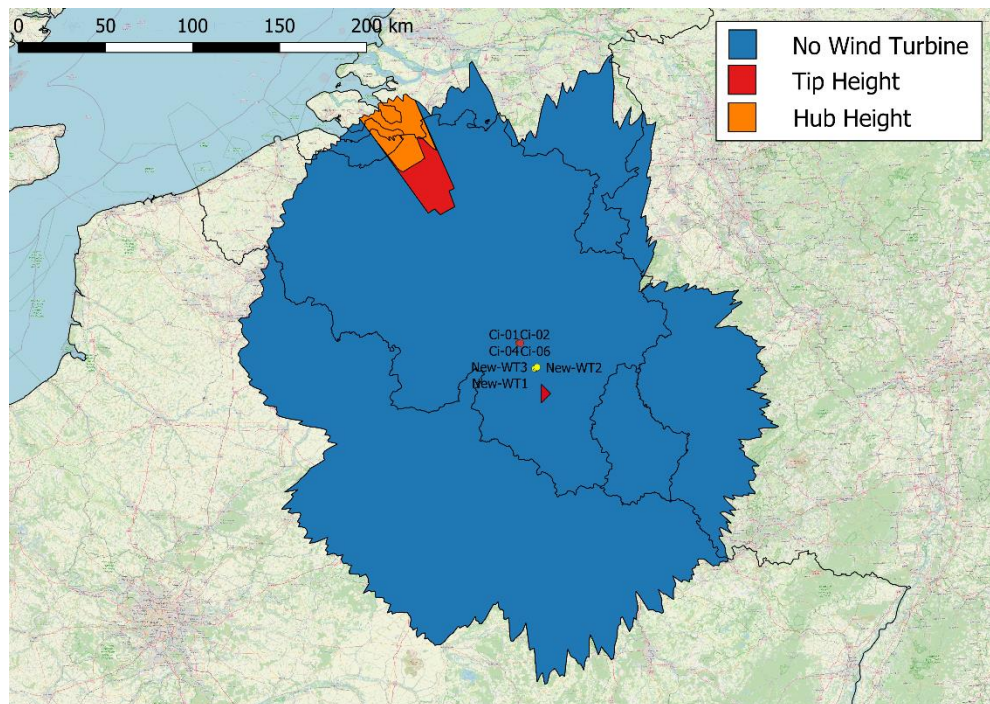


Figure 3.10 Line-of-sight coverage diagram for a target at 3000 ft AMSL as seen from the MSSR. All five existing nearby and three newly planned turbines are taken into account.

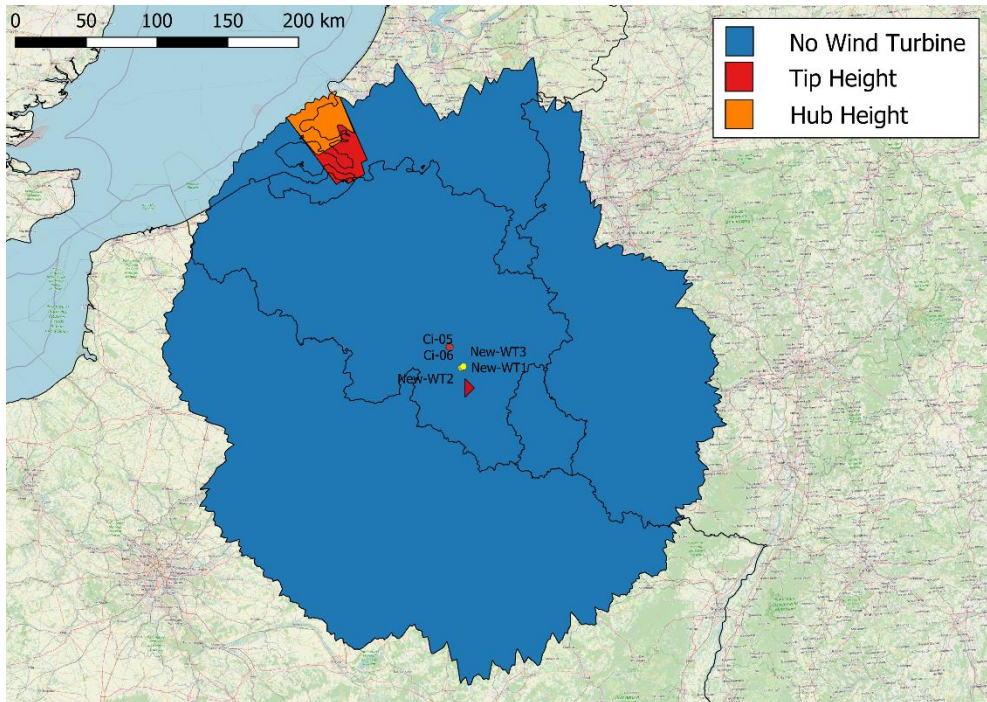


Figure 3.11 Line-of-sight coverage diagram for a target at 5000 ft AMSL as seen from the MSSR. All five existing nearby and three newly planned turbines are taken into account.

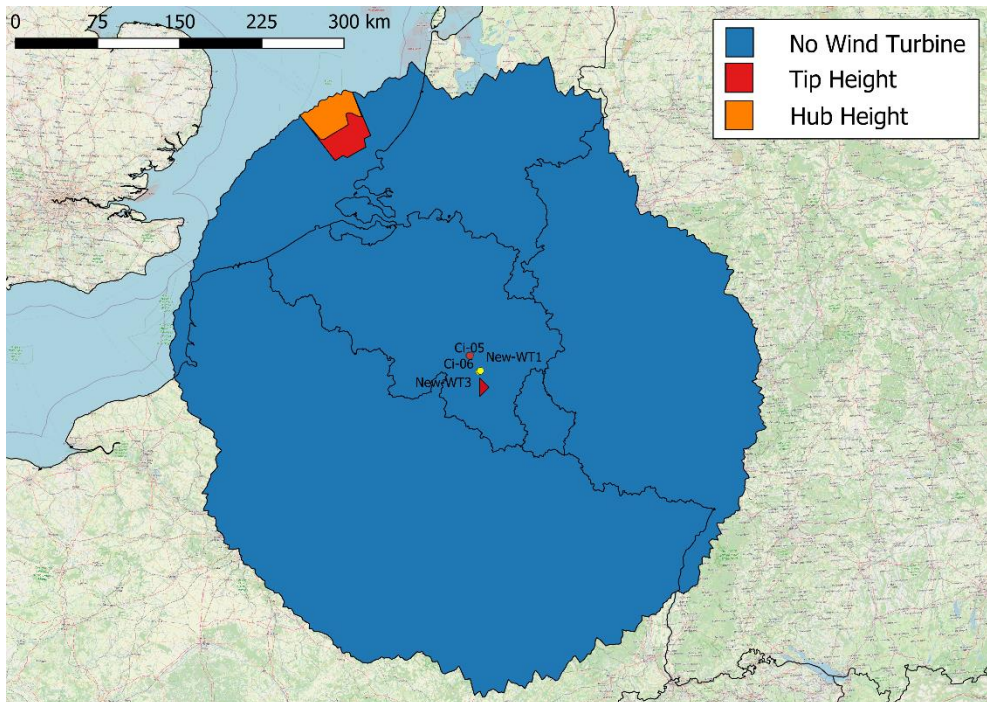


Figure 3.12 Line-of-sight coverage diagram for a target at 10000 ft AMSL as seen from MSSR. All five existing nearby and three newly planned turbines are taken into account.

### 3.3 Results of the OBE calculations

As stated earlier, the presence of an obstacle (like a mountain, building or wind turbine) between the MSSR antenna and the target can cause an error in the estimation of the bearing to the target. In this section, the extent of this bearing error is calculated using a model developed by TNO, in which the method described section 3.1 was implemented.

In this section, the OBE calculations are presented for an MSSR at Zaventem. For the orange and red areas, shown in the many figures in Section 3.2, OBE calculations were carried out. The OBE in the case of the newly planned wind turbine is determined. The OBE for each area is presented in two different figures for the planned wind turbine, resulting in a total of four figures.

Note that the OBE calculations are valid for all flight levels shown in the LoS coverage diagrams in the previous section. We only need to do one calculation for all red areas and one for all orange areas.

#### 3.3.1 OBE – Orange Area

In Figure 3.13 the OBE for the MSSR as a function of azimuth for the orange area in the previous results is presented similar to Figure 3.6, i.e. the area where the errors originate from the mast and the nacelle. As can be seen, the OBE fluctuates quite rapidly with azimuth angle. It therefore makes sense to look at the envelope of the graphs. Also, only the absolute value of the error is interesting. In Figure 3.14 we therefore present the same graphs in a slightly different manner. In these figures, the absolute OBE is grouped per azimuth sector of 1°. For each sector the value of the 50<sup>th</sup>, 90<sup>th</sup> and 100<sup>th</sup> percentile are shown in red, orange and grey, respectively. The standard deviation of the OBE is shown as a black dotted line.

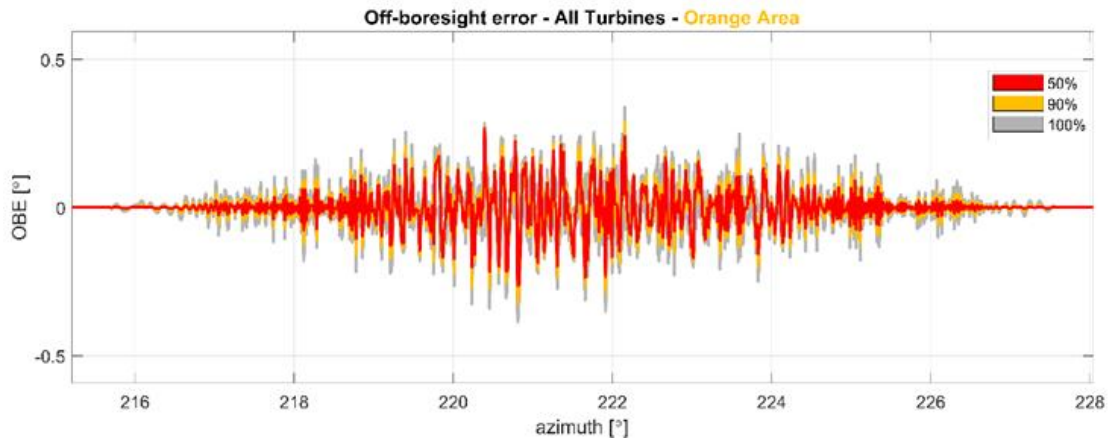


Figure 3.13 The off-boresight error as a function of azimuth for the MSSR and the ten planned turbines, in the orange areas of the figures shown in Section 3.2, i.e. the area where the errors originate from the mast and nacelle. The maximum absolute error in the orange areas is 0.39°. The azimuth sector influenced by the wind farm ranges from approximately 217° to 226° as seen from the MSSR.

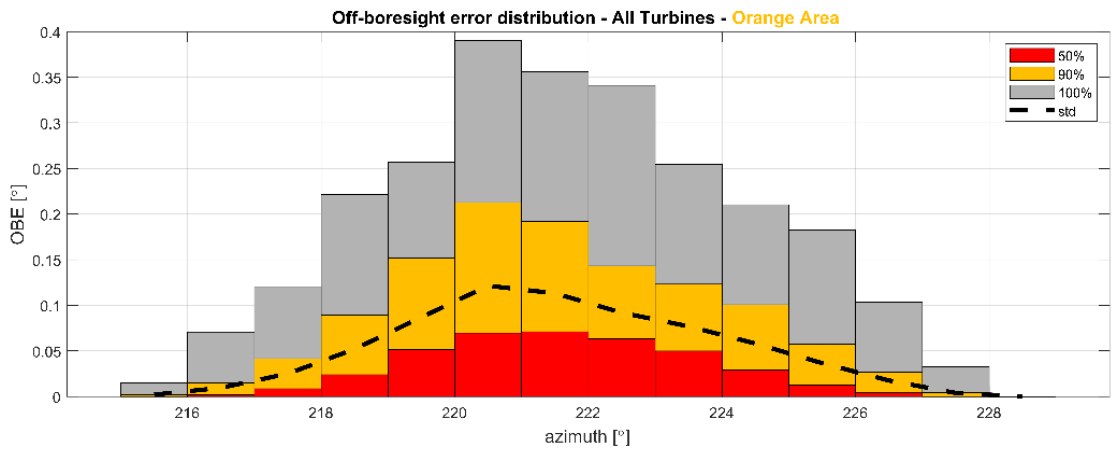


Figure 3.14 The cumulative distribution of the absolute off-boresight error per azimuth sector of 1.0° when the planned turbines are considered. For each azimuth sector the values at the 50<sup>th</sup>, 90<sup>th</sup> and 100<sup>th</sup> percentile are shown, as well as the standard deviation (1  $\sigma$ ) corresponding to a percentile of 68%, assuming a normal distribution of the errors. The maximum OBE in the orange area of 0.39° occurs at an azimuth of 220° - 221°. However, as the 90th percentile indicates, in 90% of the cases, the maximum OBE in this sector will be less than 0.22°. In 50% of the cases the maximum OBE in this sector is less than 0.07°.

### 3.3.2 OBE MSSR – Red Area

In Figure 3.15 the OBE for the MSSR as a function of azimuth in red areas is presented, *i.e.*, the area where the errors originate from the blade standing in the upright direction. In Figure 3.16 the absolute OBE is grouped per azimuth sector of 1°.

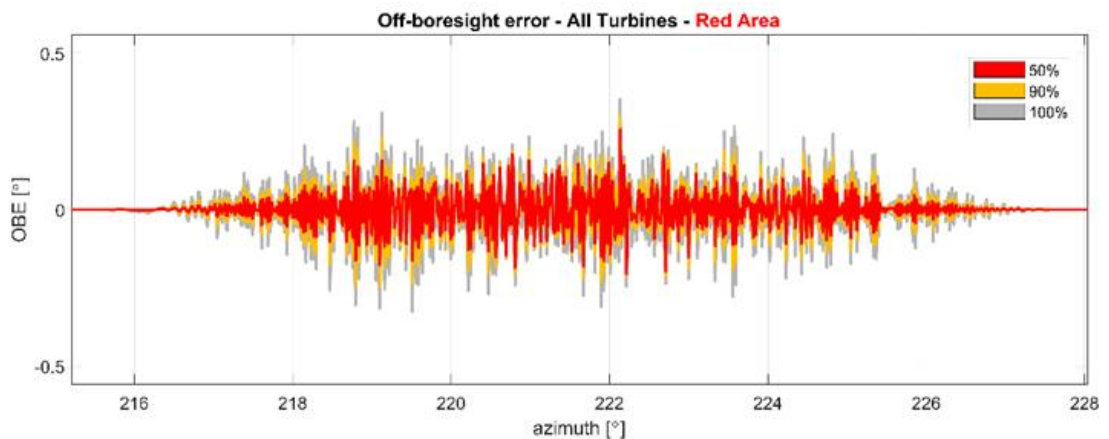


Figure 3.15 The off-boresight error as a function of azimuth for the MSSR and the ten planned turbines, in the red areas of the figures shown in Section 3.2, *i.e.* the area where the errors originate from the mast and nacelle. The maximum absolute error in the red areas is 0.35°. The azimuth sector influenced by the existing wind farm ranges from approximately 217° to 227° as seen from the MSSR.

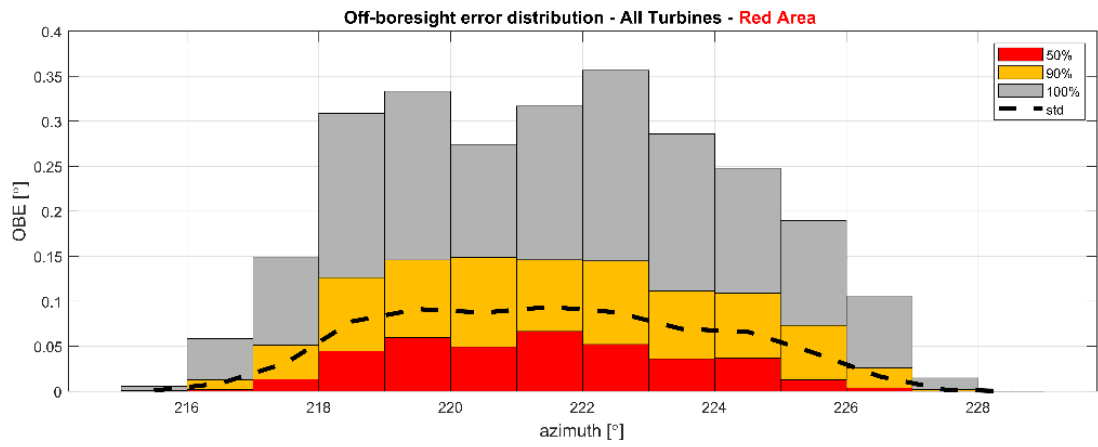


Figure 3.16 The cumulative distribution of the absolute off-boresight error per azimuth sector of 1.0° when the planned turbines are considered. The maximum OBE in the red area of 0.36° occurs at an azimuth of 222° - 223°. However, as the 90th percentile indicates, in 90% of the cases, the maximum OBE in this sector will be less than 0.14°. In 50% of the cases the maximum OBE in this sector is less than 0.05°.

# 4 Required input parameters

## 4.1 Radar (PSR & MSSR) Parameters

Table 4.1 shows the primary radar parameters that are required in order for TNO to model the radar. TNO has established good relations with a number of radar manufacturers. Due to this, TNO has a number of models ready and available. These radars include:

- › Hensoldt ASR-NG
- › Hensoldt ASR-S
- › Raytheon ASR-10SS standard version;
- › Raytheon ASR-10SS upgraded version;
- › Raytheon ASR-23SS standard version;
- › Raytheon ASR-23SS upgraded version;
- › Selex ATCR-33K;
- › Terma Scanter 4002 Infill radar;
- › Terma Scanter 2202 radar;
- › Terma Scanter 5202 radar;
- › Thomson-CSF Medium Power Radar (MPR) military long range 3D radar;
- › Thales STAR 2000 standard version;
- › Thales STAR 2000 including Wind Farm Filter (WFF);
- › Thales SMART-S Mk2;
- › Thales SMART-L EWC (GB) military long range 3D radar.

For these radar types, TNO only requires the site depending parameters, such as antenna tilt, waveguide losses and high-low short-long switching schemes.

For other radar types a new radar model has to be developed. The information required for this activity is listed in Table 4.1. If this information cannot be obtained, TNO can select, if required, the radar parameter based on its expertise.

Table 4.1: Required primary radar parameters

Item	Parameter	Unit	Value
1.	Transmit peak power	kW	
2.	Pulse compression	n.a.	yes/no
3.	Pulse duration stagger (different pulse durations)	n.a.	yes/no
4.	Pulse duration stagger strategy	n.a.	pulse to pulse or burst to burst
5.	Duration uncompressed pulse(s)	µs	
6.	Pulse compression ratio(s) (in case of pulse compression)	-	
7.	PRF stagger	n.a.	yes/no
8.	Number of pulses per burst (in case of PRF stagger from burst to burst)	-	
9.	PRF(s)	Hz	
10.	RF stagger	n.a.	yes/no
11.	RF stagger strategy	n.a.	pulse to pulse or burst to burst

Item	Parameter	Unit	Value
12.	RF(s)	MHz	
13.	Antenna elevation pattern(s) on transmit	-	diagram
14.	Antenna elevation pattern(s) on receive	-	diagram
15.	Azimuth beamwidth (one way, between -3 dB points)	°	
16.	Antenna polarisation(s)	n.a.	H/V/C
17.	Antenna gain(s)	dBi	
18.	Antenna tilt angle	°	
19.	Antenna position (WGS84, Lambert, Rijksdriehoekstelsel or other local geographic projection)	°	
20.	Altitude electrical centre antenna AMSL	m	
21.	Altitude electrical centre antenna w.r.t. local terrain	m	
22.	Ground level at antenna	m	
23.	Beam switch scheme angle versus distance (in case of beam switching on receive)	° & m	
24.	Scan duration	s	
25.	Receiver instantaneous bandwidth	MHz	
26.	Receiver noise figure	dB	
27.	Waveguide losses on transmit (+ rotating joint, transitions)	dB	
28.	Waveguide losses on receive (+ rotating joint, transitions)	dB	
29.	Digital signal processing	n.a.	yes/no
30.	Type of Doppler filtering	n.a.	Pulse canceller or Doppler filter bank or both
31.	Pulse canceller details (nr. pulses involved, weights, etc.)	n.a.	
32.	Doppler processing gain	dB	
33.	Doppler filter bank details (response curves or weights)	dB	
34.	Range quant depth	m	
35.	CFAR type (CA/CAGO/CASO/OS or others)	n.a.	
36.	CFAR, number of guard cells	-	
37.	CFAR, number of window cells	-	
38.	False alarm probability	-	
39.	Processing losses (range straddling, CFAR losses, Doppler straddling)	dB	
40.	Operational use		stand-alone or networked

Apart from the parameters listed above, a (filled in) Blake-chart would be very helpful as well.

Table 4.2: Required (monopulse) secondary radar parameters

Item	Parameter	Unit	Value
1.	Transmit peak power	kW	
2.	Antenna transmit and receive gain	dBi	
3.	Antenna patterns, elevation as well as azimuth, transmit as well as receive	dBc	
4.	Antenna tilt angle	°	
5.	Antenna vertical and horizontal dimensions	m	
6.	Number of antenna elements	-	
7.	Type of monopulse (Amplitude or Phase)	-	
8.	Antenna position (lat/long in either WGS84, Lambert, Rijksdriehoek or other datum)	°	
9.	Altitude electrical centre antenna AMSL	m	
10.	Altitude electrical centre antenna w.r.t. local terrain	m	
11.	Ground level at antenna	m	

## 4.2 Wind turbine parameters

The dimensions of the wind turbines used within PERSEUS are derived from 3D CAD drawings. Over the past years TNO has gathered CAD drawings from all major wind turbine manufacturers such as Enercon, Goldwind, EWT, Lagerwey, Nordex, Senvion, Siemens-Gamesa and Vestas. For this purpose we have established a number of Non-Disclosure Agreements. Parameters that are derived from these drawings are listed in Table 4.3.

Table 4.3: Wind turbine parameters

Quantity	Description	Unit
Tower dimensions		
Height	Height of the tower	m
Bottom width	Diameter of tower at base	m
Top width	Diameter of tower at the nacelle	m
Nacelle dimensions		
Length	Length of side face of nacelle	m
Width	Width of front face of nacelle	m
Height	Height of nacelle	m
Rotor blades		
Length	Length from rotor to blade tip	m
Width	Maximum width of the blade	m

Alternative, if a wind turbine manufacturer has not yet been selected, the assessment can be performed by applying a wind turbine with worst-case outer dimensions. Based on the generated power, hub height and rotor diameters TNO will select the worst case dimension from its wind turbine database.

Defence, Safety & Security

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**TNO** innovation  
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## Appendix F: Schiphol Amsterdam Case Study



# Detailed Engineering Assessment

Onno van Gent and Duije Deurloo  
20 November 2025

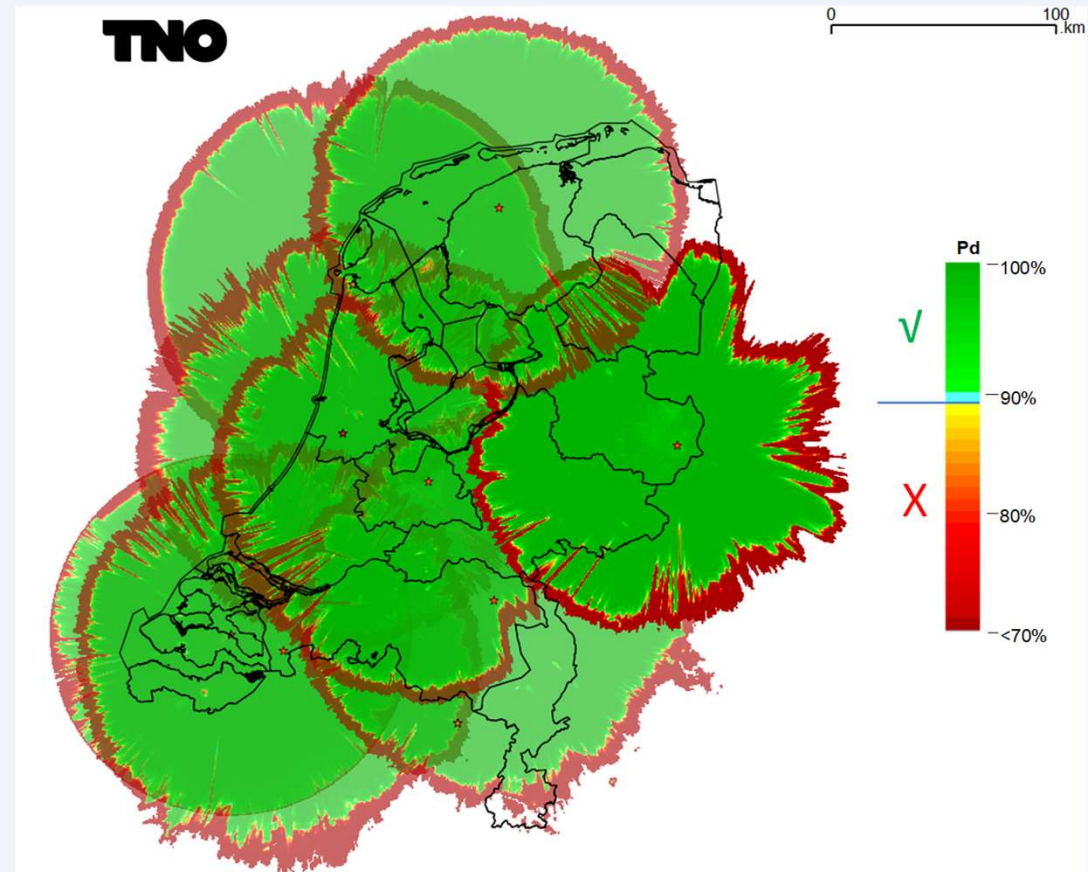
# More than 30 Years of Experience

- Defence Research Laboratory established at Waalsdorpervlakte, The Hague before WW2.
- In 1982 Defence Research merged into TNO organisation
- TNO is a not-for-profit organisation established by law
- Since 1995 TNO investigates the effects of wind turbines on Defence radars and develops assessment methods.
- Most recent method is PERSEUS, sponsored by Ministry of Defence as well as Ministry of Economics.
- TNO have developed PERSEUS Tooling Capabilities for primary and secondary radar simulations.



# Situation in The Netherlands

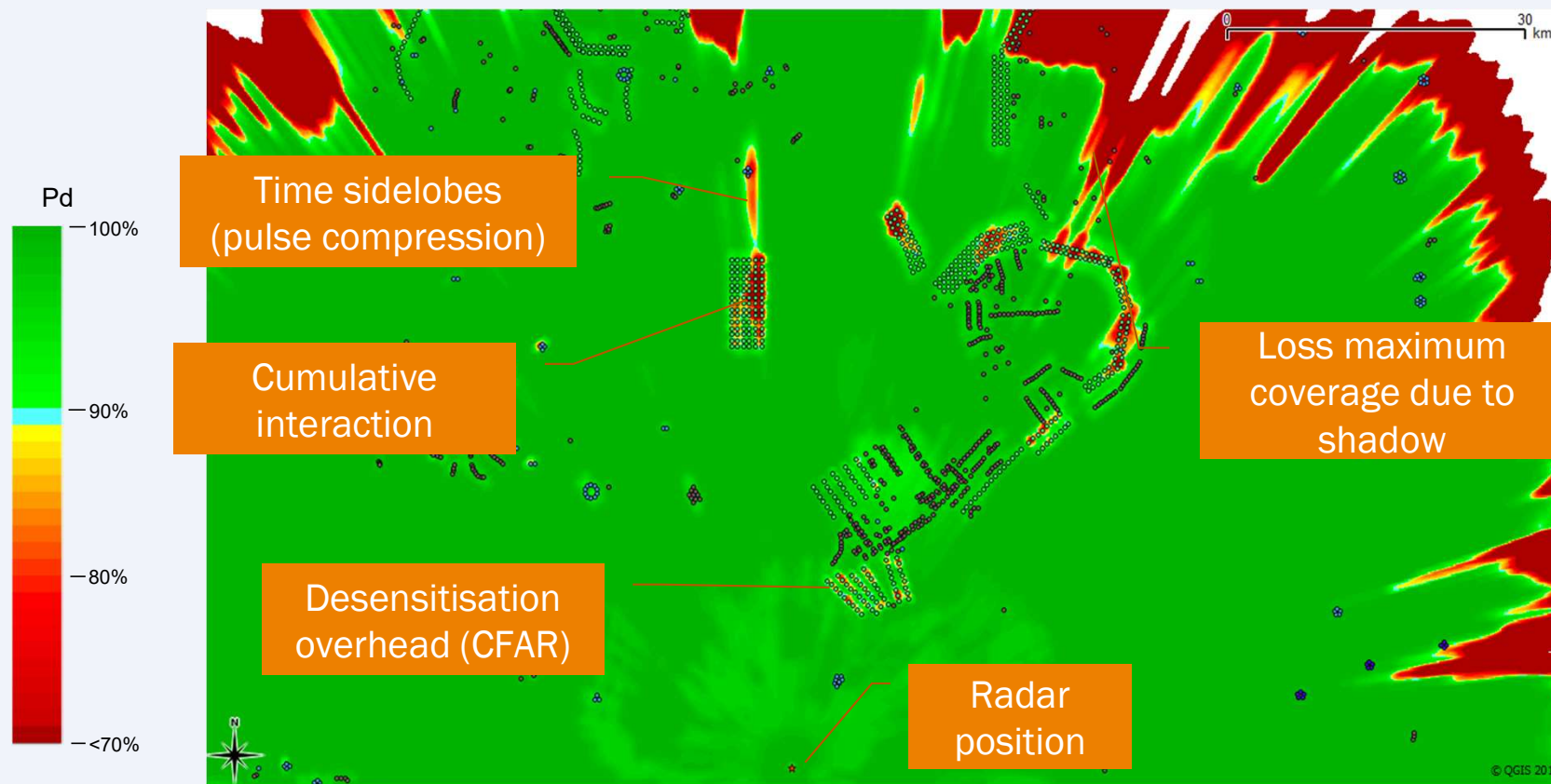
- Combined (fused) common primary (right) and secondary picture using ARTAS.
- Each new windfarm in The Netherlands needs to be assessed by TNO using PERSEUS.
- The results are then evaluated by the Military and/or Civil Air Control.



# TNO's Roles

- Formal role in The Netherlands:
  - Each wind turbine above a certain tip height needs to be assessed by TNO.
  - An assessment is performed for the Air Traffic Control and the Fighter Control radars against the Dutch Standards.
  - Wind farm developers need to pay for this.
  - TNO can assist wind farm developers to come up with a plan that meets the Dutch standards.
- Consultancy role to support the Dutch government and Civil Air Control:
  - Identify potential issues with respect to air coverage and assist mitigation measures.
- International references:
  - Support wind farm developers in Belgium, Denmark, Finland, Sweden, France, Switzerland, United Kingdom and Australia.
  - ANSPs: In Belgium we also performed studies for Skeyes (Belgium ANSP) in order for them to update their regulations

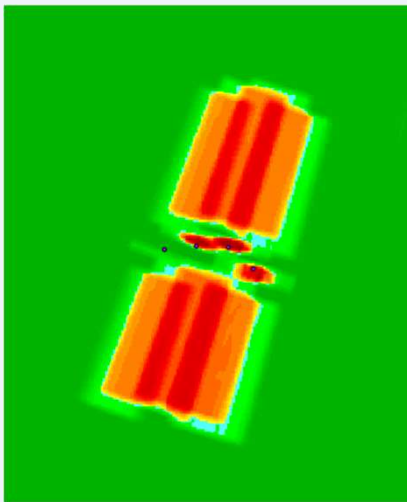
# Primary Radar Clutter Simulations



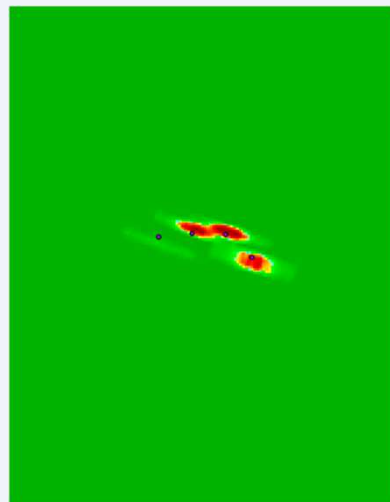
# Primary Radar Clutter Simulations

- Actual examples:
  - Raytheon ASR-10SS: Parallel processing high and low beam & CFAR peak picking
  - Thales STAR 2000: Wind Farm Filter (WFF)
  - Thales STAR NG: Parallel processing high and low beam & WFF

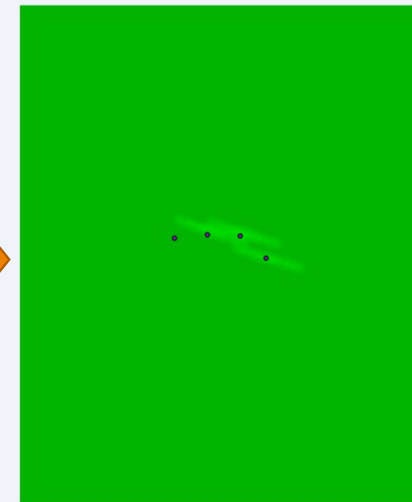
Standard (CAGO) operation  
Target at 1000 ft



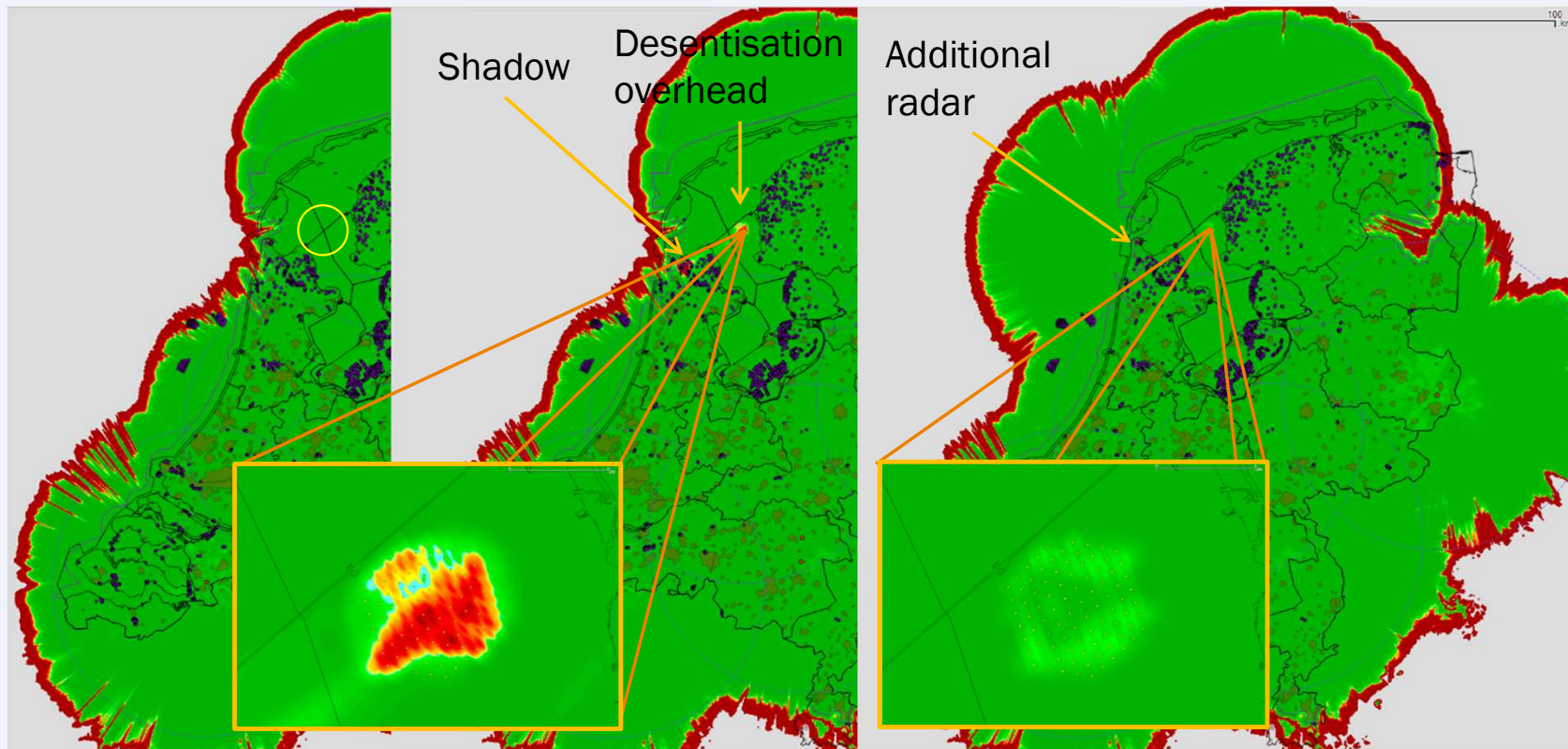
Enhanced operation  
Target at 1000 ft



Parallel processing  
high-low beams  
Target at 4000 ft

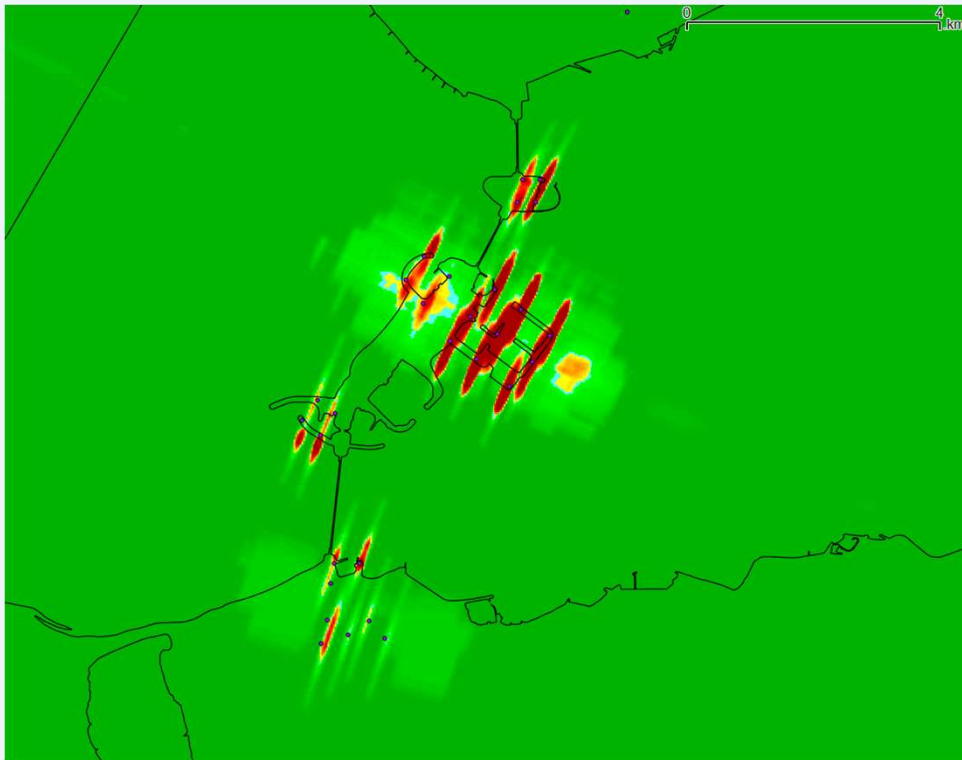


# Mitigation Measures – The Netherlands

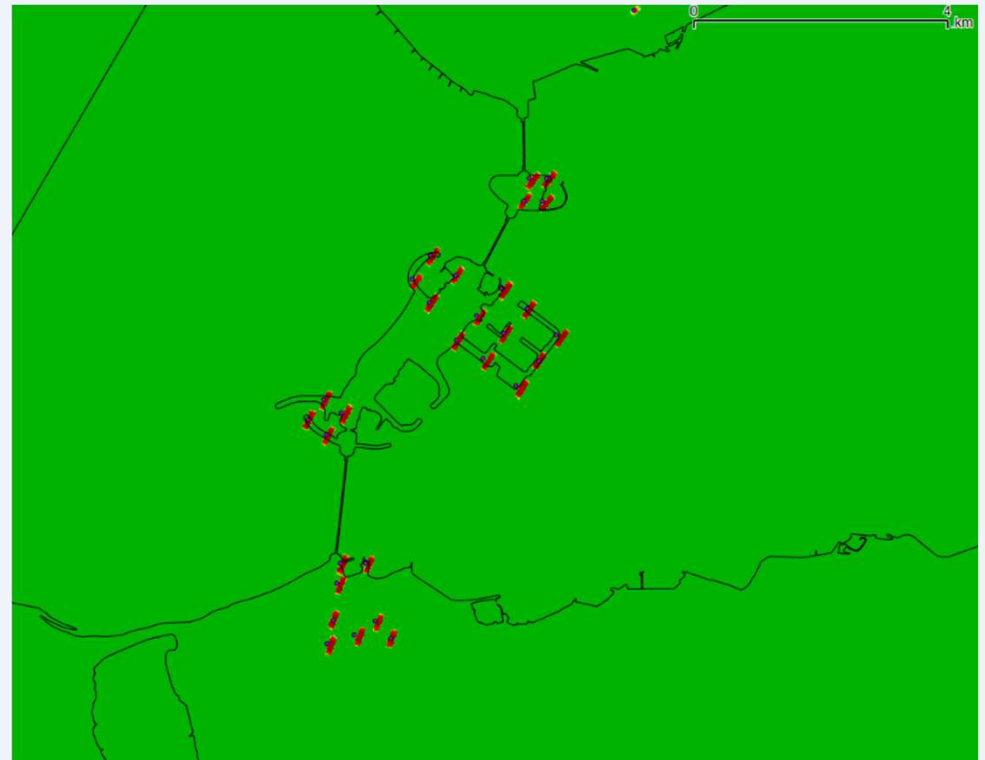


# Primary Infill Radar Simulations

Conventional ATC radar (ASR-10SS Woensdrecht)

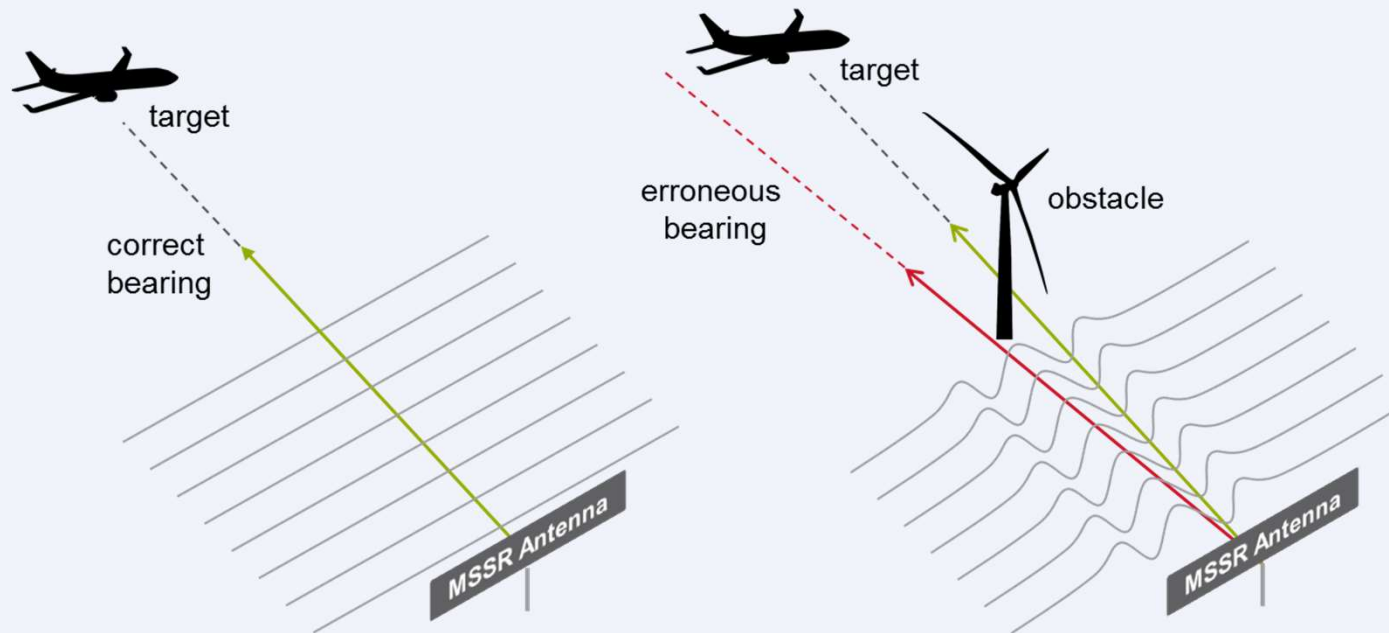


SCANTER 4002 infill radar (Wemeldinge)



# Secondary Radar Simulations

- Wind turbines, positioned between target and MSSR antenna can disturb the transponder signal, introducing an error in the bearing estimate.
- Included in PERSEUS toolkit

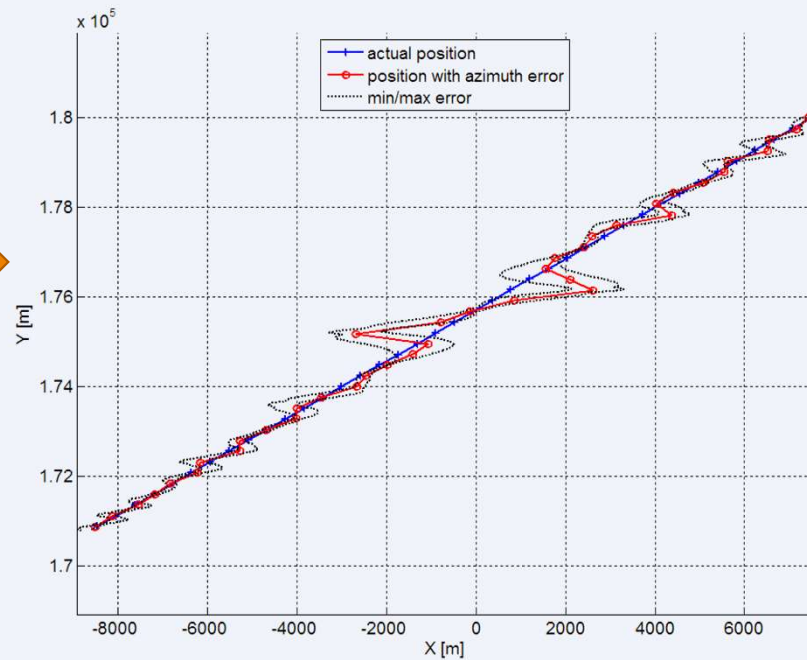


# Track Errors Simulations

- Effects of the obstacle on the MSSR at Zaventem Airport (Belgium) accurately modelled.
- The obstacle is the ATC Tower at Zaventem at approximately 2 km from the radar

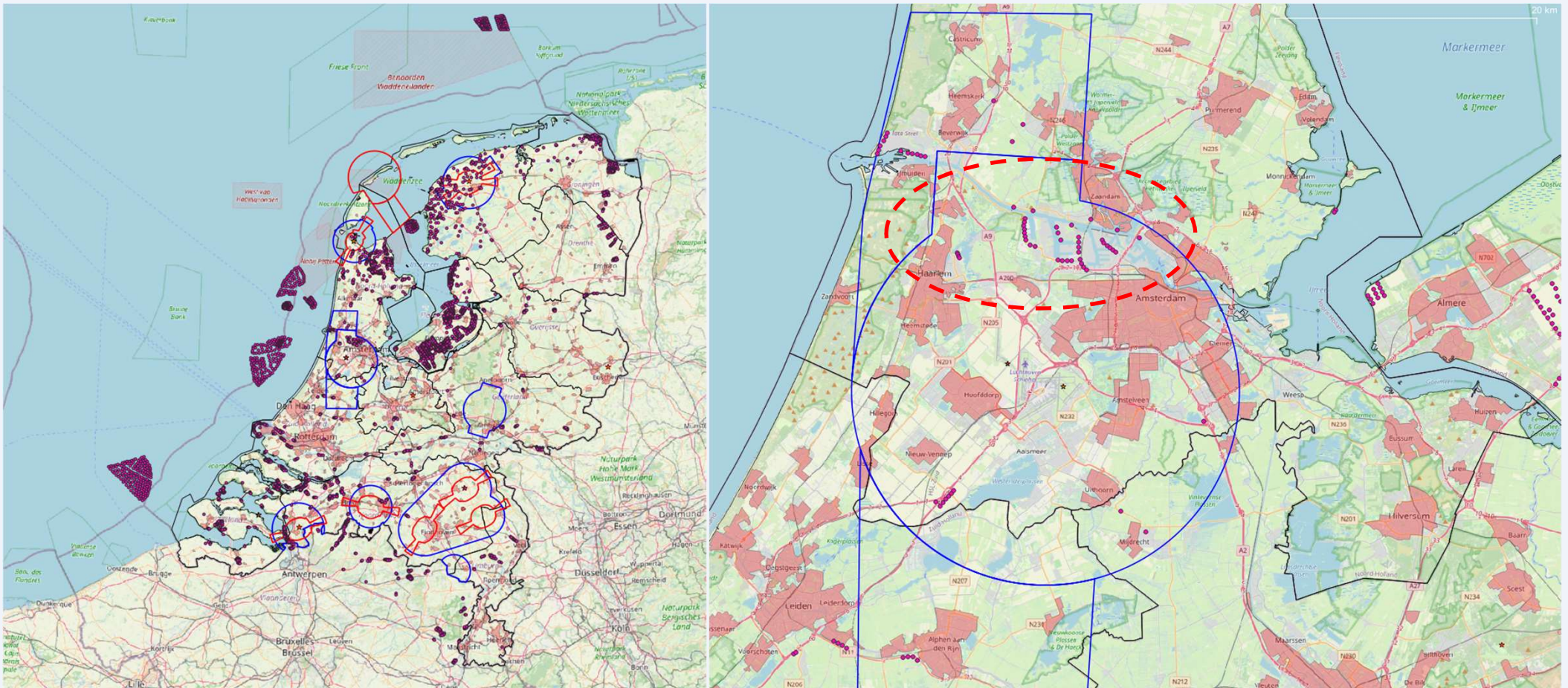


Recorded Real track at approximately 200 km from the radar



Simulated track

# Existing Wind Farms around Schiphol Amsterdam

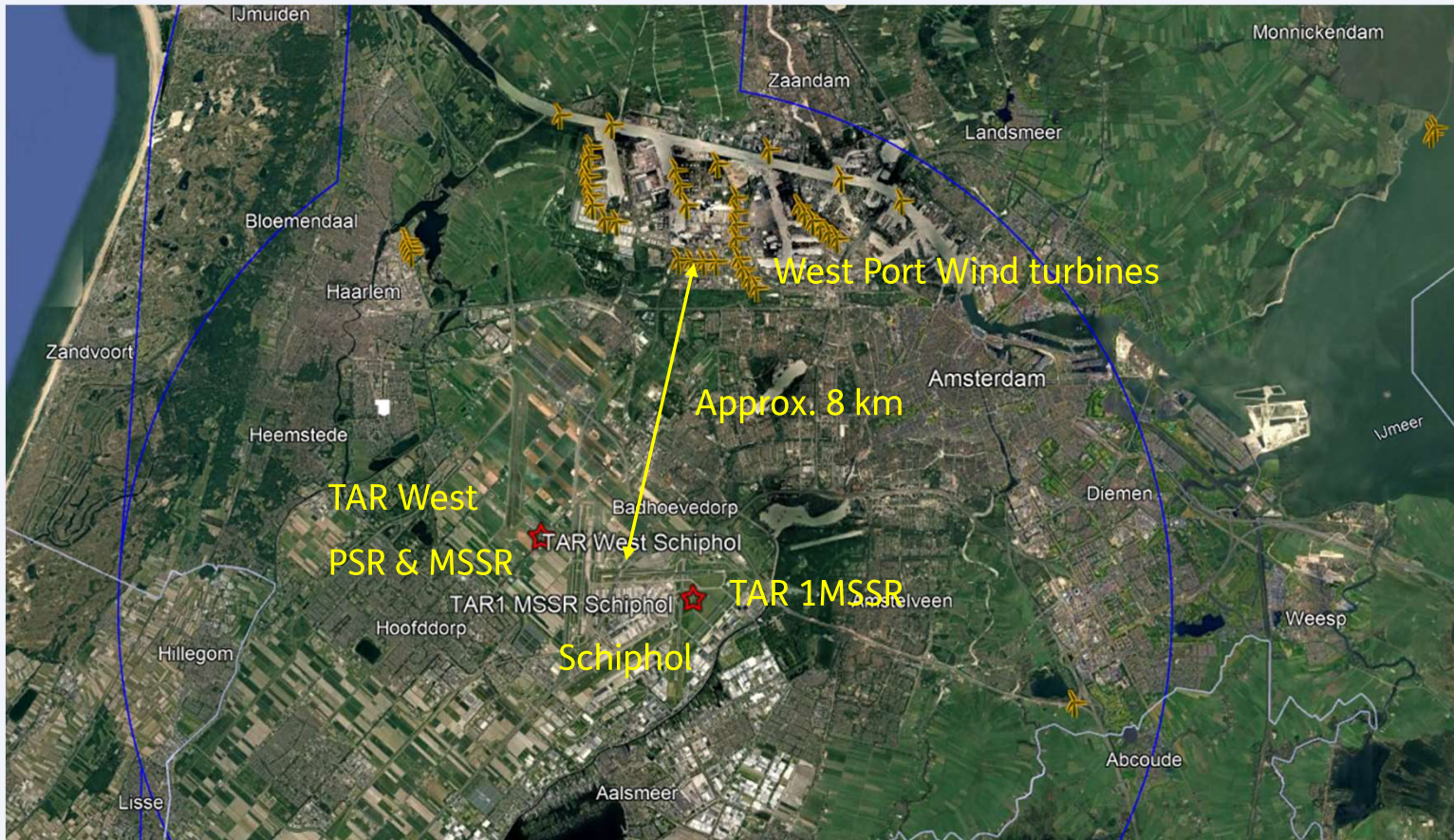


# Schiphol Airport Wind Farm Assessment

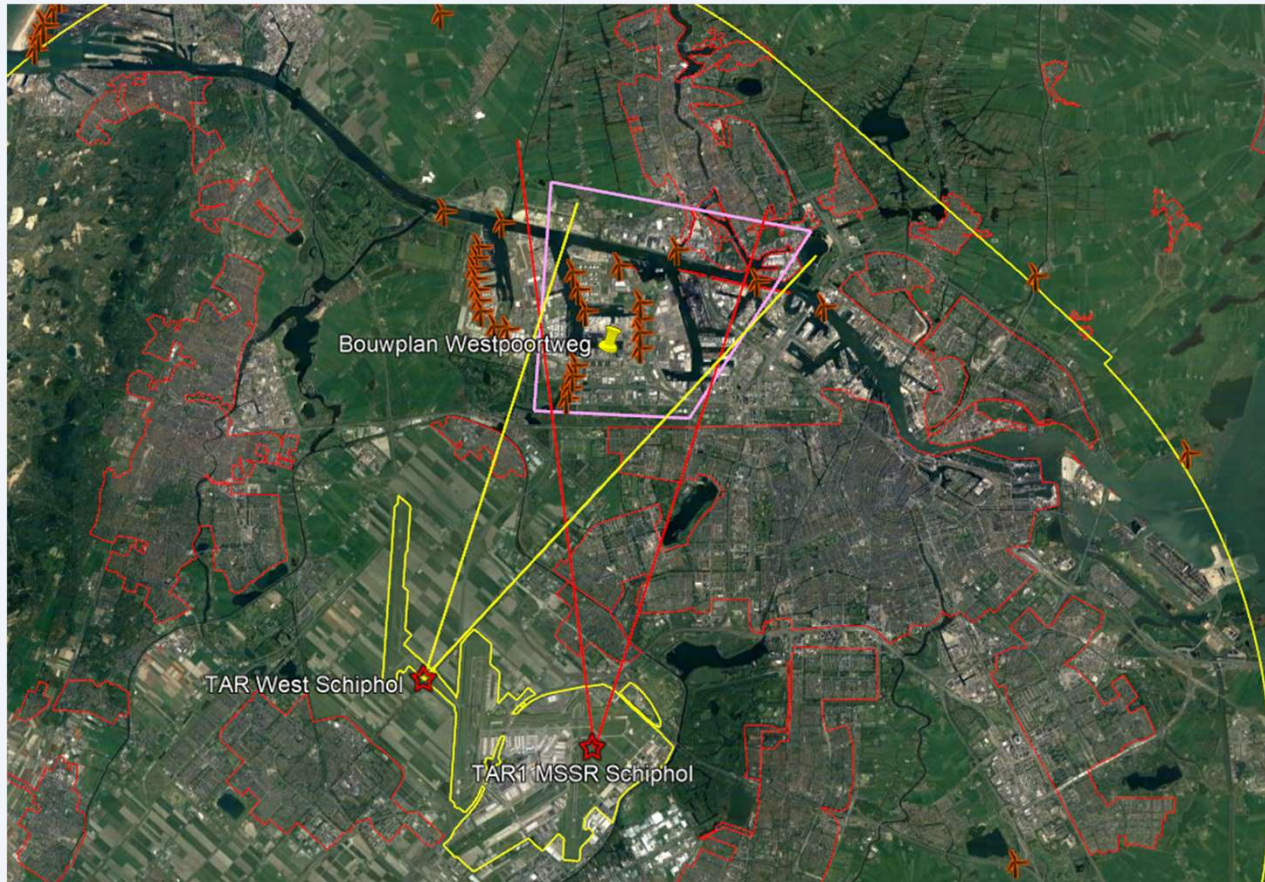
- The Port of Amsterdam had plans to extend the existing windfarm with four new turbines in the West Port area.
- However, the wind turbine lay approximately 8 km north of the International Airport Schiphol.
- Therefore, the Dutch Civil Air Control (LVNL) were concerned about the impact these wind turbines could have on their primary and secondary radars.
- Basic EUROCONTROL requirements:
  - Within APP minimum separation 3 NM. This requires a RMS position accuracy less than 300 m
  - Within ACC minimum separation 5 NM. This requires a RMS position accuracy less than 500 m
- This has to be realised with at least two MSSRs!



# Wind Farm - North of Schiphol Airport

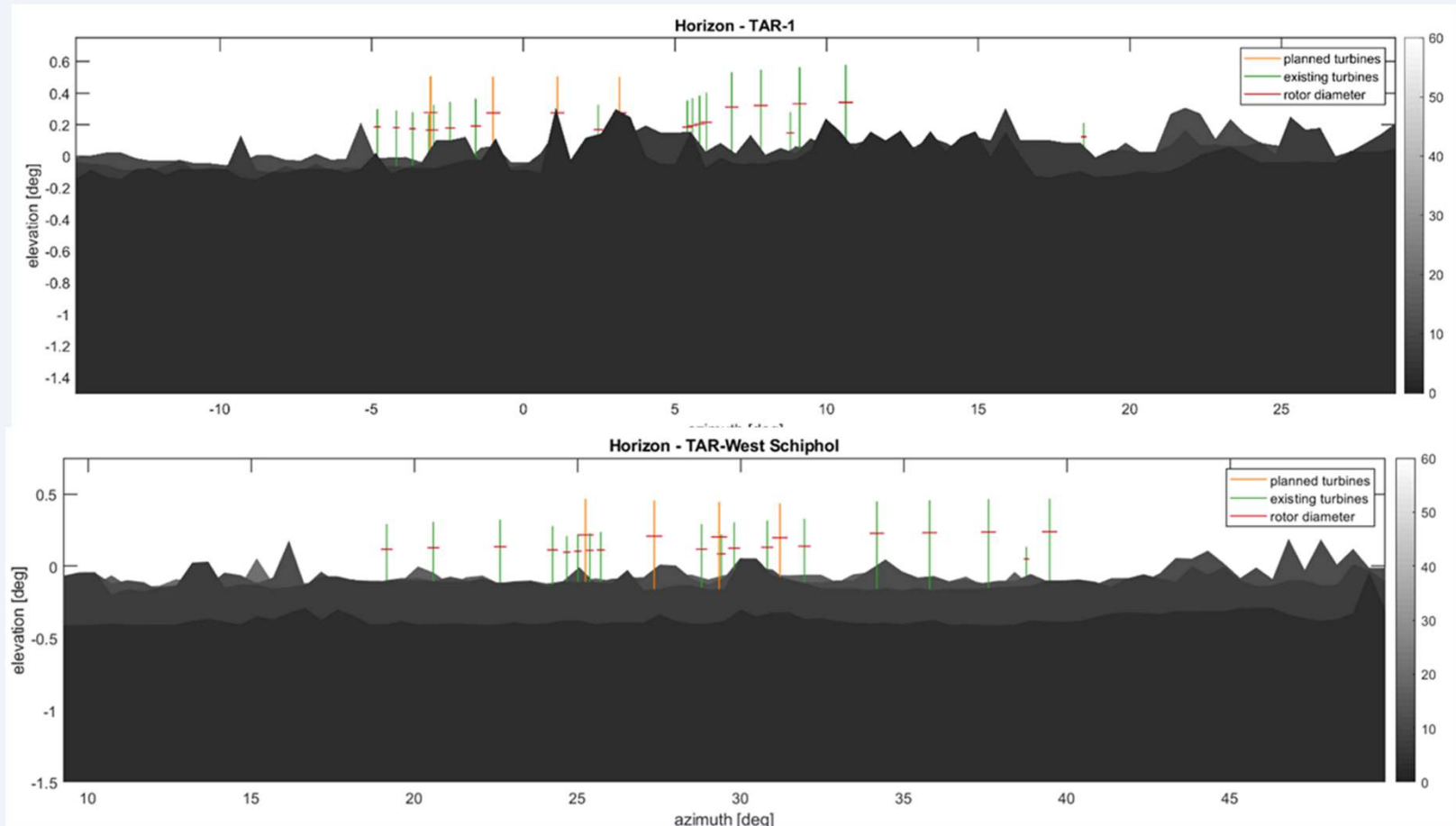


# Schiphol Airport Radars - Existing and New Farms

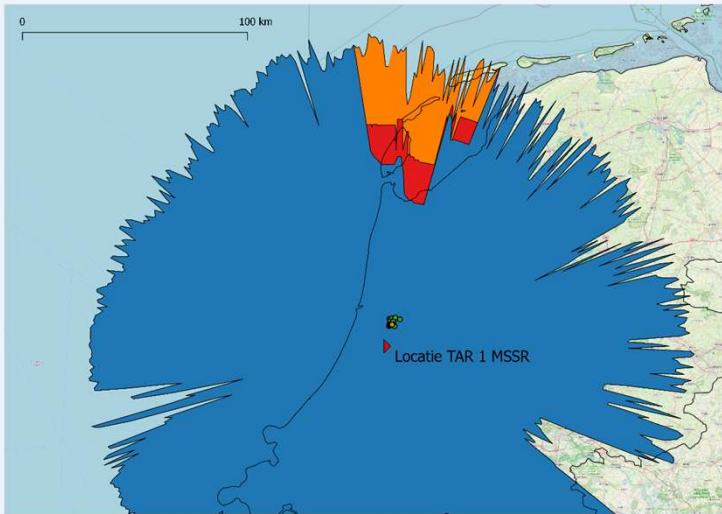


# Schiphol Radars Line of Sight investigation

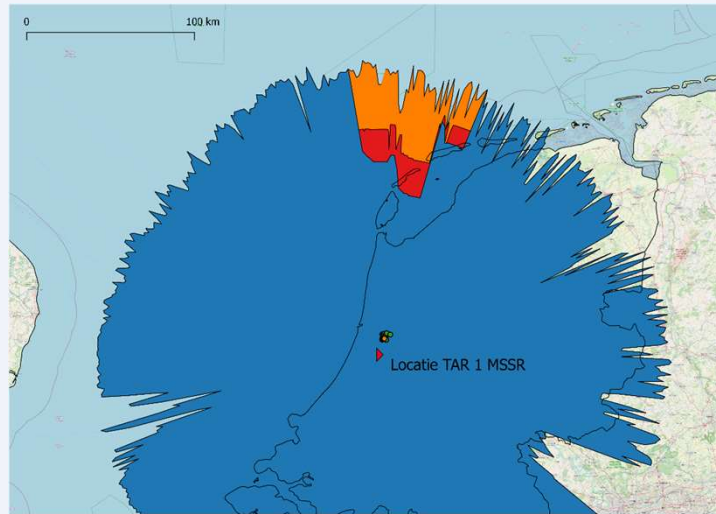
- View from Terminal Approach Radar 1 (TAR 1)
- View from Terminal Approach Radar West (TAR West)
- Note, due to the different viewpoint of each MSSR they appear at different angles



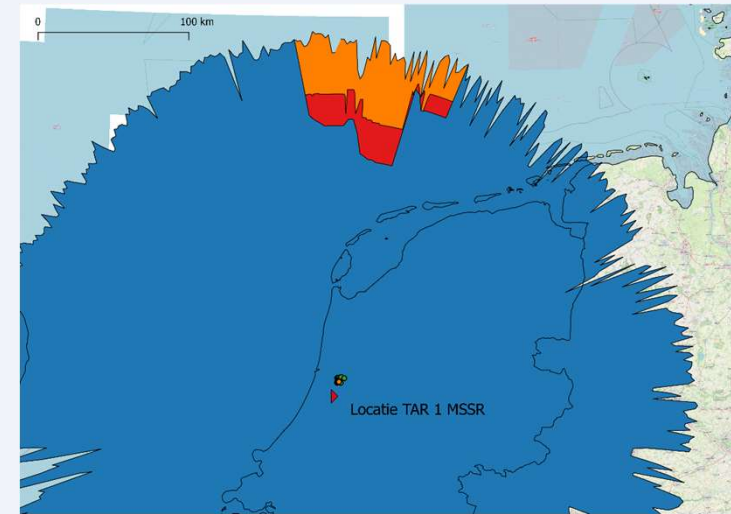
# Schiphol TAR 1 Radar – Baseline Coverage



3000 ft

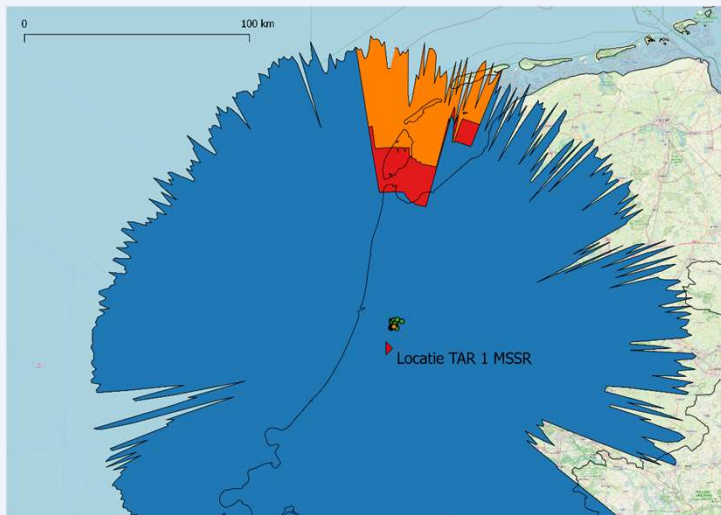


5000 ft

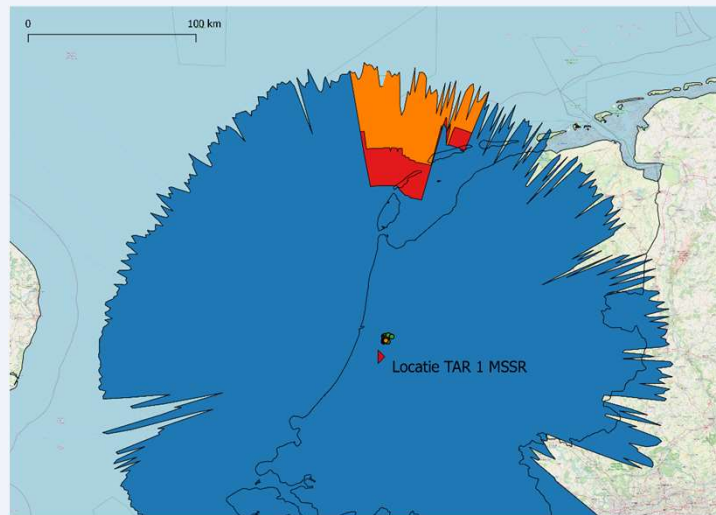


10000 ft

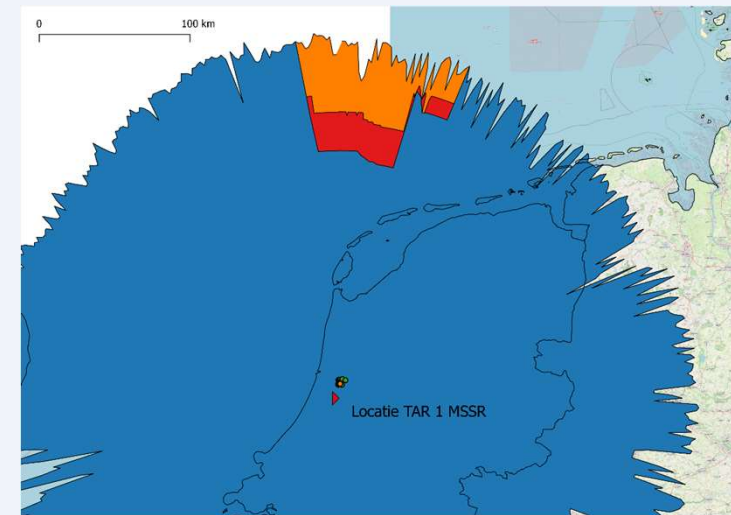
# Schiphol TAR 1 Radar – Coverage with New Turbines



3000 ft

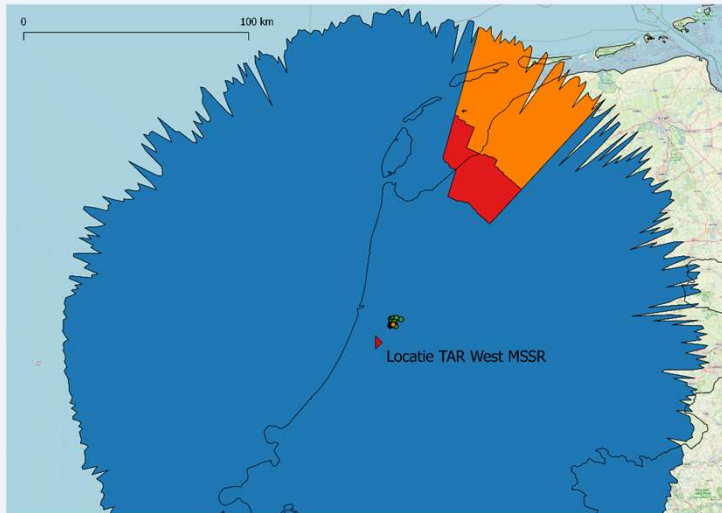


5000 ft

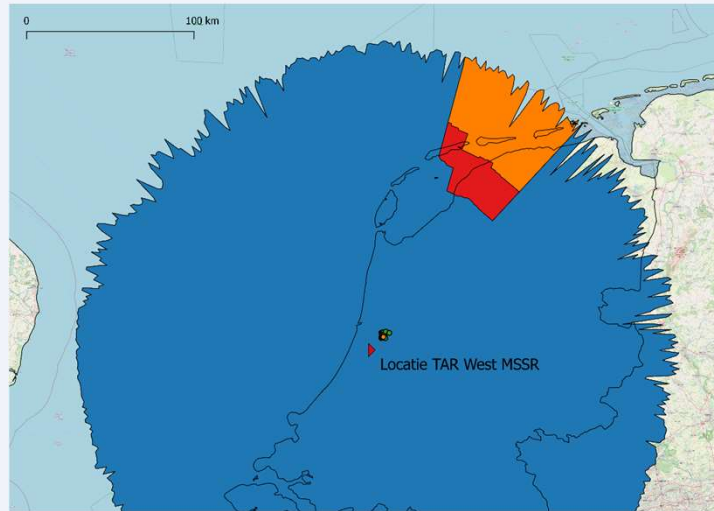


10000 ft

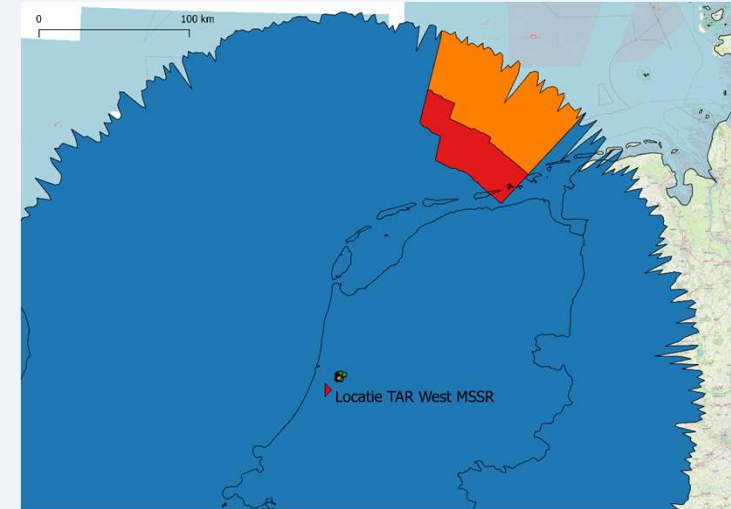
# Schiphol TAR West Radar – Coverage with New Turbines



3000 ft



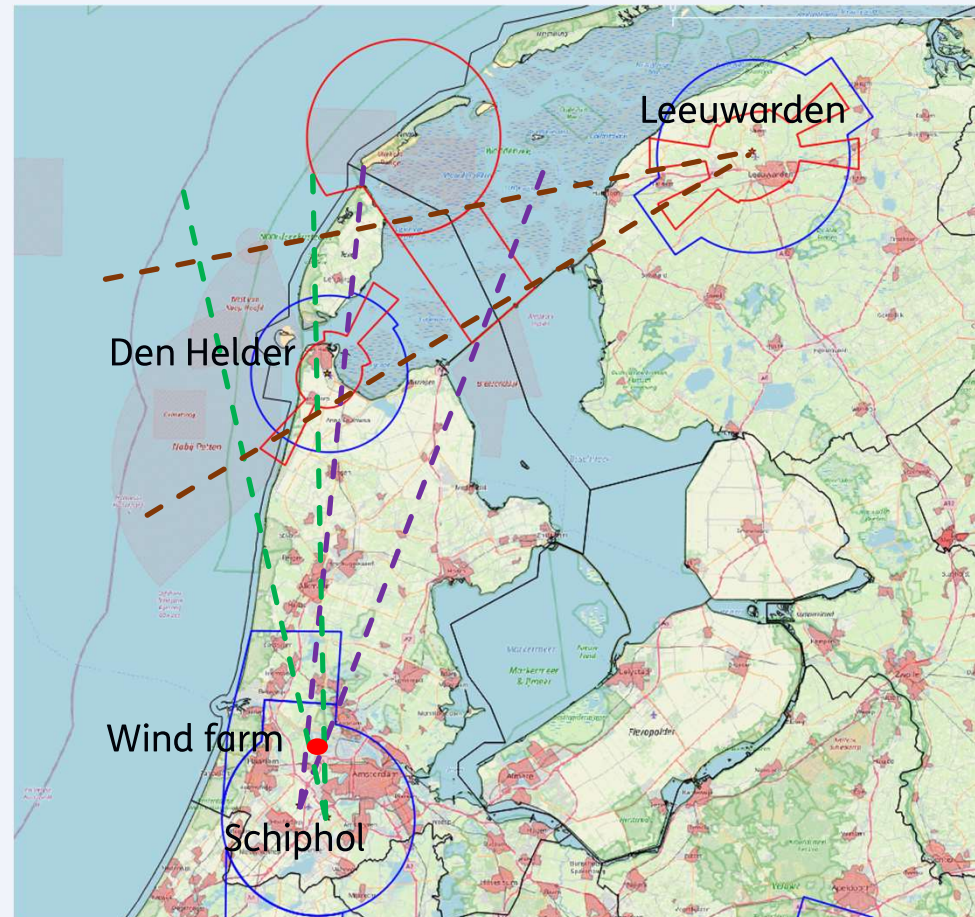
5000 ft



10000 ft

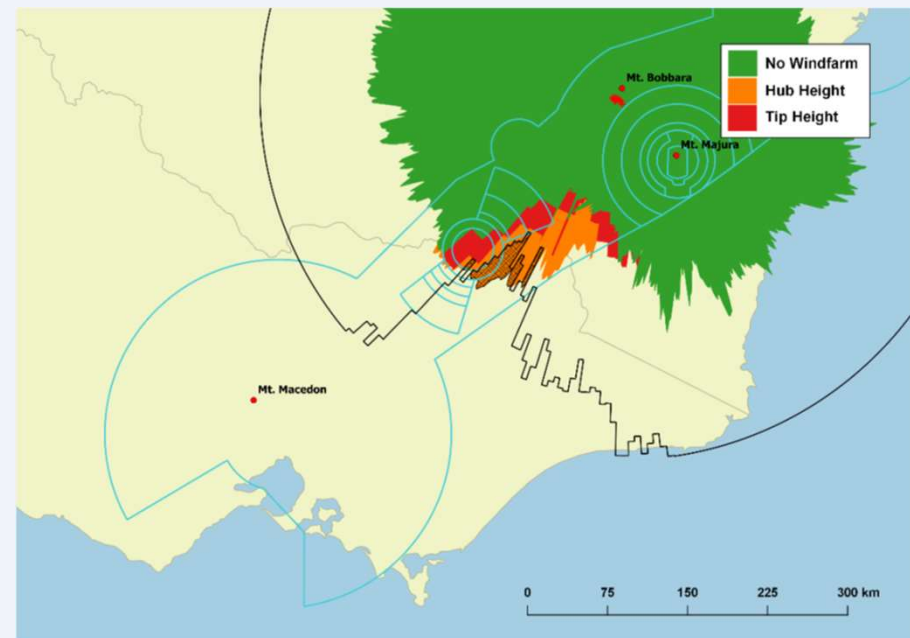
# Wind Farm Effects and Mitigation

- Due to the new wind turbines errors start to occur north of Den Helder.
- Due to the different angle of view of the TAR 1 and TAR West different sectors are influenced.
- The dual MSSR coverage north of Den Helder is maintain by the MSSR at Leeuwarden.

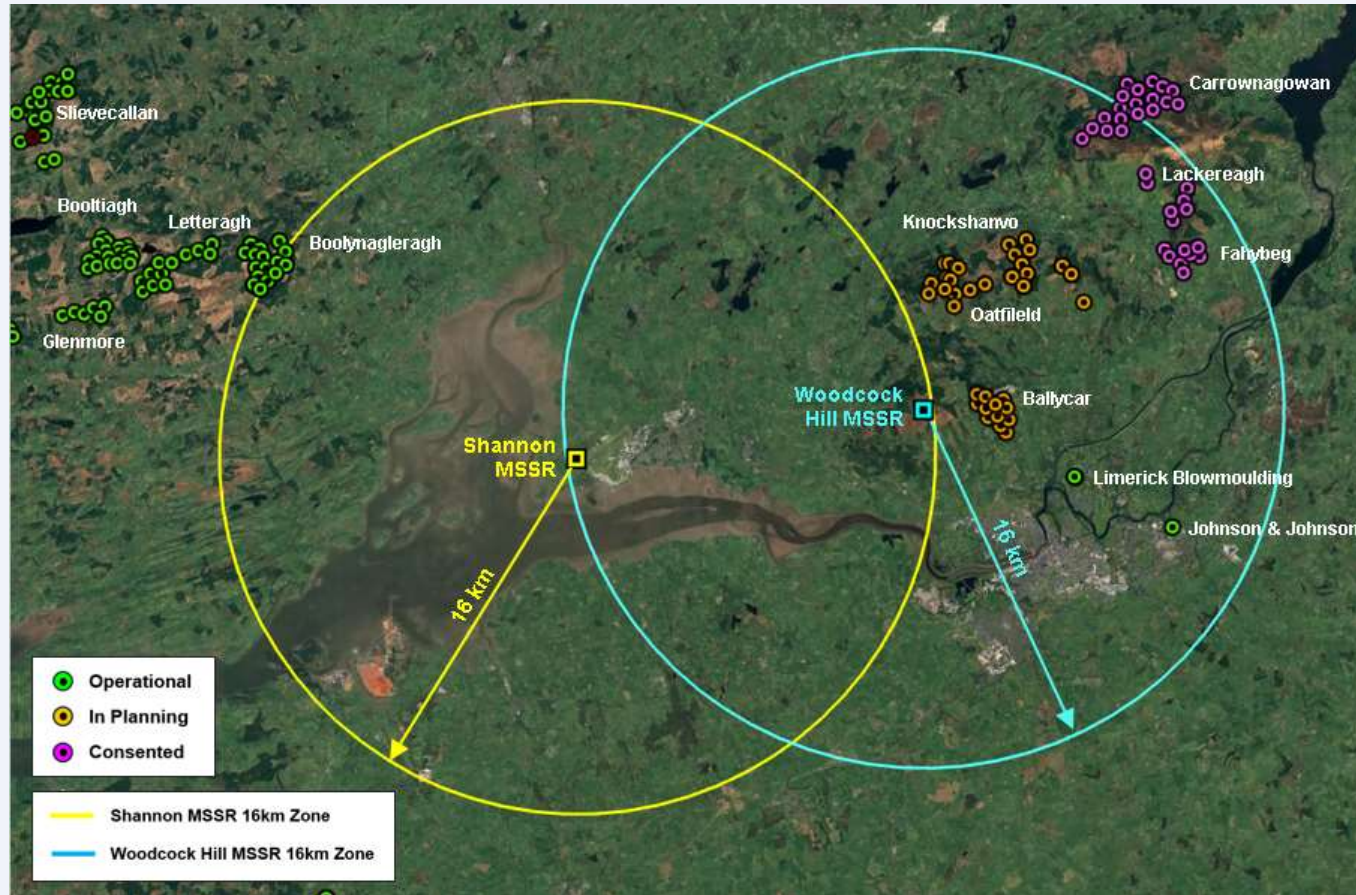


# Australia – MSSR Wind Farm Impact Mitigation

- The OBE errors that occur in the orange and red areas are translated into position errors.
- With this, a contour can be drawn indicating where the minimum position accuracies are still met.



# East Clare Wind Farm Developments



Theme name Place text here

# Thank you for your attention



Detailed Engineering Assessment for the  
Secondary Radar at Woodcock Hill

# Detailed Engineering Assessment due to Wind Turbines at Knockshanvo

TNO 2025 R13102 – 21 January 2026

# Detailed Engineering Assessment due to Wind Turbines at Knockshanvo

Detailed Engineering Assessment for the  
Secondary Radar at Woodcock Hill

Author(s)	Onno van Gent, Detmer Bosma
Classification report	TNO Intern
Title	TNO Intern
Report text	TNO Intern
Number of copies	Number of copies
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Sponsor	Ai Bridges Limited
Project name	DEA MSSR Woodcock Hill Oatfield
Project number	060.67849/01.02.01

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# Abbreviations

## Abbreviation Meaning

ACP	Azimuth Change Pulse
AGL	Above Ground Level
AFB	Air Force Base
AMSL	Above Mean Sea Level
ARB	Auxiliary Reference Burst
ASR	Airfield Surveillance Radar
CAGO	Cell Averaging Greatest Of
CFAR	Constant False Alarm Rate
CTR	Controlled Traffic Region
CUT	Cell Under Test
DEM	Digital Elevation Model
EGM96	Earth Gravitational Model 1996
LVA	Large Vertical Aperture
MRB	Main Reference Burst
MSSR	Monopulse Secondary Surveillance Radar
NASA	National Aeronautics and Space Administration
NGSP	Next Generation Signal Processor
OBE	Off-sight Bearing Error
PSR	Primary Surveillance
RCS	Radar Cross section
RPM	Revolutions Per Minute
SSR	Secondary Surveillance Radar
SRTM	Shuttle Radar Topography Mission
SWG	Slotted Wave Guide
TNO	Netherlands Organisation for Applied Scientific Research
VCC	Vertical Clutter Cancellation
WC	Worst-case
WT	Wind Turbine
WFF	Wind Farm Filter
WGS84	World Geodetic System 1984

# 1 Introduction

The performance of radar systems can be negatively influenced by wind turbines in their vicinity. EUROCONTROL has issued guidelines, on how to assess the potential impact of wind turbines [1]. Within these guidelines different zones around the radar are defined. A Detailed Engineering Assessment (DEA) for the primary radar is required at distances to the wind turbines ranging from 500 m to 15 km (zone 1). In the zone ranging from 15 km to the instrumented range of the primary radar (zone 2), a so-called Simple Engineering Assessment (SEA) is required in case there is line of sight. For the secondary radars, a DEA needs to be performed in case the wind turbines are located closer than 16 km from the radar.

FuturEnergy Knockshanvo Designated Activity Company (DAC) has plans to build the Knockshanvo Wind Farm comprising of nine wind turbines. All wind turbines will have a tip height of 185 m. The closest wind turbine is located at a distance of approximately 6 km from the secondary radar at Woodcock Hill, so inside the 16 km distance from the radar. Therefore for the secondary radar a DEA is required following the EUROCONTROL guidelines. DAC has used the technical assistance of Ai Bridges Limited and the aviation specialists Cyrrus Limited. Ai Bridges has requested TNO to perform the DEA. Due to the fact that there is a second newly planned windfarm Oatfield, with overlapping wind turbine positions, a second DEA is performed for the combined situation.

In Section 2 the general information is given and in Section 3 the specific input parameters of the relevant wind turbines and radar for this study are given. In Section 4, we perform the DEA for the MSSR at Woodcock Hill. Finally, in Section 5 conclusions are drawn.

## 2 General Information

### 2.1 Effects of wind turbines on MSSR

The presence of wind turbines can influence the performance of MSSRs. In order to correctly interpret the results of the Line-of-Sight analysis, we address the most important issue that can arise whenever a wind farm is near a secondary radar system: bearing errors.

SSRs differ from PSRs in a number of ways. PSRs do not depend on cooperation of aircraft, they merely measure range, bearing and sometimes also elevation angle and radial velocity. SSRs demand that aircraft cooperate, *i.e.*, the aircraft actively participates in its detection.

The SSR sends out an interrogation signal at 1030 MHz. The target, carrying a radar transponder, subsequently replies by transmitting a response signal at 1090 MHz. This response contains additional information regarding the target, *e.g.*, barometric altitude (mode C) and an identity code (mode A). In the case of monopulse SSR (MSSR), the system is capable of making a precise bearing estimate of the target from a single reply signal (hence, monopulse). The bearing estimate is generally accurate within a fraction of a degree ( $\sim 0.05^\circ$ ). The presence however of an obstacle (like a mountain, building or wind turbine) between the MSSR antenna and the target can cause an error in the estimation of the bearing to the target.

In Figure 2.1 an MSSR antenna is shown, typically comprising 35 antenna elements. Below we first give a short description on how the bearing measurement is carried out and how the wind turbine influences this measurement.



Figure 2.1 The secondary radar antenna, comprising of 35 antenna elements, on top of a STAR 2000 antenna.

The bearing to a target is determined using the so-called monopulse technique. By applying different weight factors for each antenna element, two radar beams are created with the same antenna, the so-called *sum beam* and *difference beam*, see Figure 2.2. A reply is received by both beams. By comparing the signal strength in the sum beam to the signal strength in the difference beam an accurate bearing angle can be estimated. Left-right

ambiguity is solved by looking at the phase of the signal. For example, when the sum and difference beam record a pulse with the same signal strength, looking at Figure 2.2 we see that the bearing to the target must be, depending on the phase, either  $+1^\circ$  or  $-1^\circ$ .

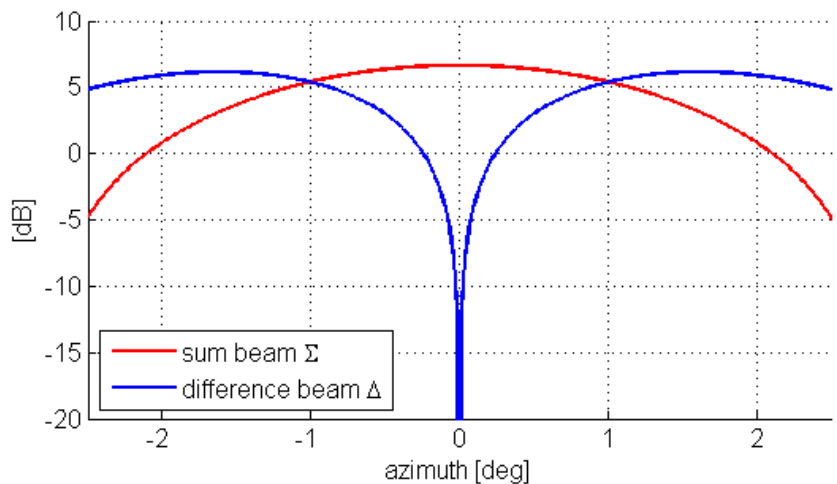


Figure 2.2 The sum beam (red) and difference beam (blue) used within the TNO model. The bearing of the target is estimated by comparing the signal strength of a single reply signal in both beams.

If a wind turbine is positioned between the target and the radar, the received electric field is distorted both in phase and in amplitude. This is illustrated in Figure 2.3. The distorted field effectively changes the weight factor at each antenna element, thus, changing the shape of the sum beam and difference beam. As the two beams are influenced differently by the wind turbine, so is the signal strength measured in both beams. Therefore, when the signal strength is compared to estimate the bearing, an error is introduced.

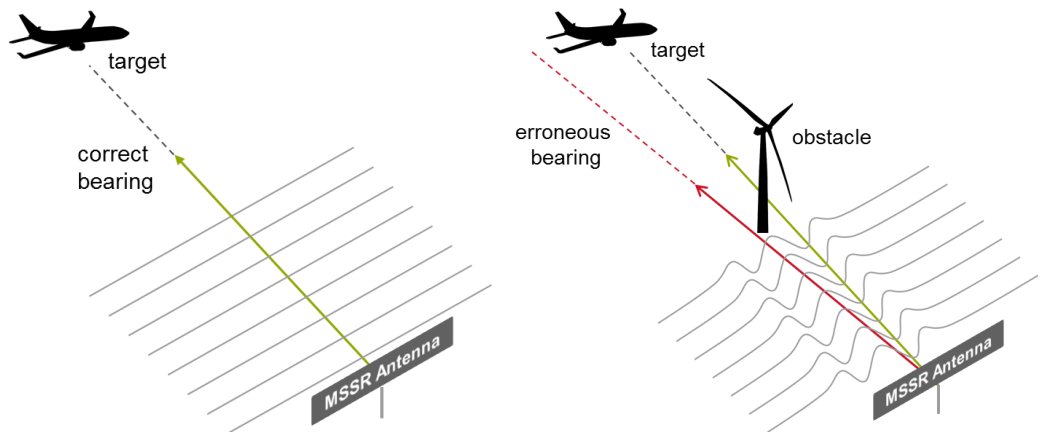


Figure 2.3 A wind turbine, positioned between target and MSSR antenna can disturb the transponder signal, introducing an error in the bearing estimate.

The bearing error as a function of azimuth angle to the target has been calculated. This will give us insight in the width of the zone in which the MSSR is influenced by the wind turbine. To estimate the bearing error we use an analytical solution for an incident plane wave on a cylinder with fixed radius and infinite length. The method calculates the phase and amplitude of the perturbed wave front on each antenna element. From this the bearing error is determined. The method is described in full in [2]. In this reference the method has been validated using real data of an MSSR partially obstructed by a metal mast of width  $\sim 2$  meter at a range of approximately 600 meter.

TNO has conducted its own validation of the method as well using real MSSR data. In this validation the MSSR is partly obstructed by an ATC tower with a maximum width of 20 meter at a range of approximately 2 km. In both cases, the calculated bearing error as a function of azimuth matched relatively well with the measured data. Figure 2.4 shows the close match between real recorded MSSR track of an aircraft at a distance around 175 km from the MSSR and the simulated data. Secondary effects at coordinates [4, 178] and [-4, 174] km appear accurately modelled as well (indicated by red arrows).

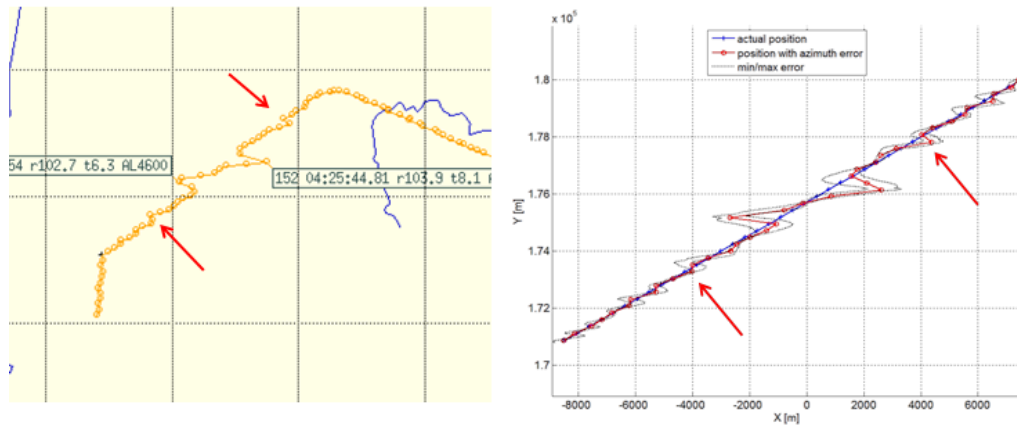


Figure 2.4 Comparison of a MSSR track recording of a real aircraft and the simulated results. Secondary effects at coordinates [4, 178] and [-4, 174] km appear accurately modelled as well (indicated by red arrows).

As mentioned, the method uses a cylinder of infinite length to model the obstacle. An infinite cylinder can be described by just a single parameter, its width. In our simulations we have chosen the width of the cylinder to be dependent on whether or not the nacelle or blades can be seen by the radar, see Figure 2.5. In the orange sector, the width of the cylinder is equal to the average of the width and length of the nacelle. In the red sector, the width of the cylinder for all visible wind turbines is set to the width of the blade, see Figure 2.5.

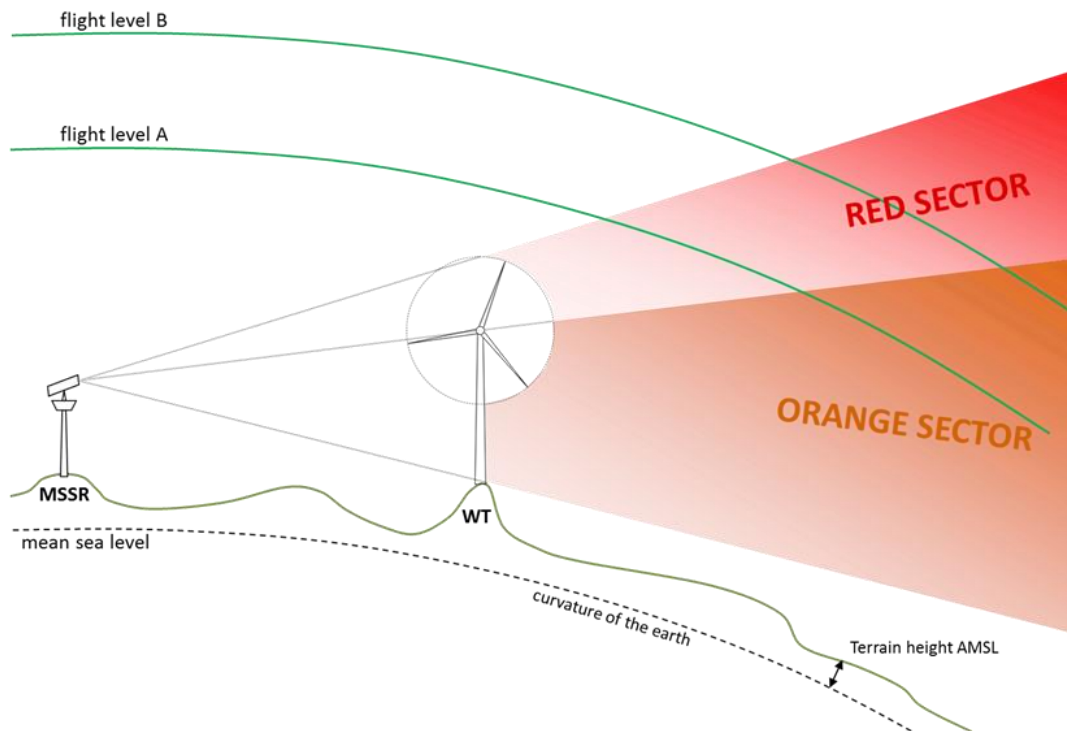


Figure 2.5 The orange and red areas, shown in the LoS coverage diagrams are in fact cuts through a volume behind the wind turbines. The calculated OBE (Off Boresight Error) is thus valid at all flight levels shown in the LoS coverage diagrams.

It is assumed that there is always a wind turbine blade with a vertical orientation. The full tip height of the turbine is used in the analysis. As there is not always a wind blade directed vertically, this is a worst case assumption.

Furthermore, the applied method describes the incoming signal as a plane wave (as depicted in the left image of Figure 2.3). The approximation of the incoming radiation as a plane wave is valid in case the distance between the target and the obstacle is sufficiently large. To see whether the plane wave approximation is valid, we calculate at which distance the phase difference between the two ends of the wind turbine blade is equal to half a wavelength. The path difference  $\Delta r$  from one end of the blade to the other can be approximated by  $\Delta r = L^2/2R$ , where  $L$  is the length of the blade and  $R$  is the range. Setting  $\Delta r$  equal to half a wavelength,  $\lambda/2$ , and filling in for this example  $L = 60.7$  meter, we find  $R = 13$  km at 1090 MHz. We see that the incoming wave for a target at 13 km behind the obstacle already resembles a plane wave quite closely. For targets at larger distances the resemblance will be even better. For targets closer than 13 km to behind the wind turbine, the estimated bearing error is a first order approximation.

Regarding the geometry of the situation, we take into account two parameters: (1) the azimuth angle to the target, relative to the obstacle and (2) the orientation of the radar antenna at the moment that the transponder reply is received. Given a wind turbine at a certain azimuth angle,  $\alpha$ , we let the target move from  $\alpha - 4^\circ$  to  $\alpha + 4^\circ$  in 501 steps. At more than  $4^\circ$  azimuth from the wind turbine the error reduces rapidly to values much smaller than the accuracy of the MSSR (typically  $0.05^\circ$ ). For each position of the target, the radar antenna is rotated over  $3^\circ$ , from  $-1.5^\circ$  to  $1.5^\circ$ , where  $0^\circ$  corresponds to the antenna looking directly at the target. For each geometry the disturbed electric field is calculated. This is done for each

(visible) wind turbine in the wind farm separately. Subsequently, all disturbed fields are summed and the bearing error for the total field is calculated.

A typical example of the Off-Boresight Error (OBE) for a single obstacle (i.e., cylinder width 25 meter) at a range of 3 km is shown in Figure 2.6. The obstacle is located at an azimuth angle of 218.5°. At a given azimuth angle, the error is in 100% of the cases contained within the two grey lines, in 90% of the cases between the two orange lines. The OBE at a given azimuth angle is thus not a single number, but lies in the range defined by the two lines of the same colour. The reason this happens, is that, as mentioned above, the geometry between the rotating antenna, target and obstacle can differ for a target at a given azimuth. The grey line thus gives the upper limit of the bearing error to be expected at a given azimuth angle. This is the case when the radar antenna is in the least favourable orientation when receiving the reply signal.

As can be seen in the figure below the OBE caused by a single obstacle is point symmetrical around the azimuth to the obstacle. Directly behind the obstacle, the error is zero. In this case the sum and difference beams are equally disturbed, resulting in no error of the estimated azimuth angle. Note that in the case of multiple obstacles at different ranges, the symmetry is broken.

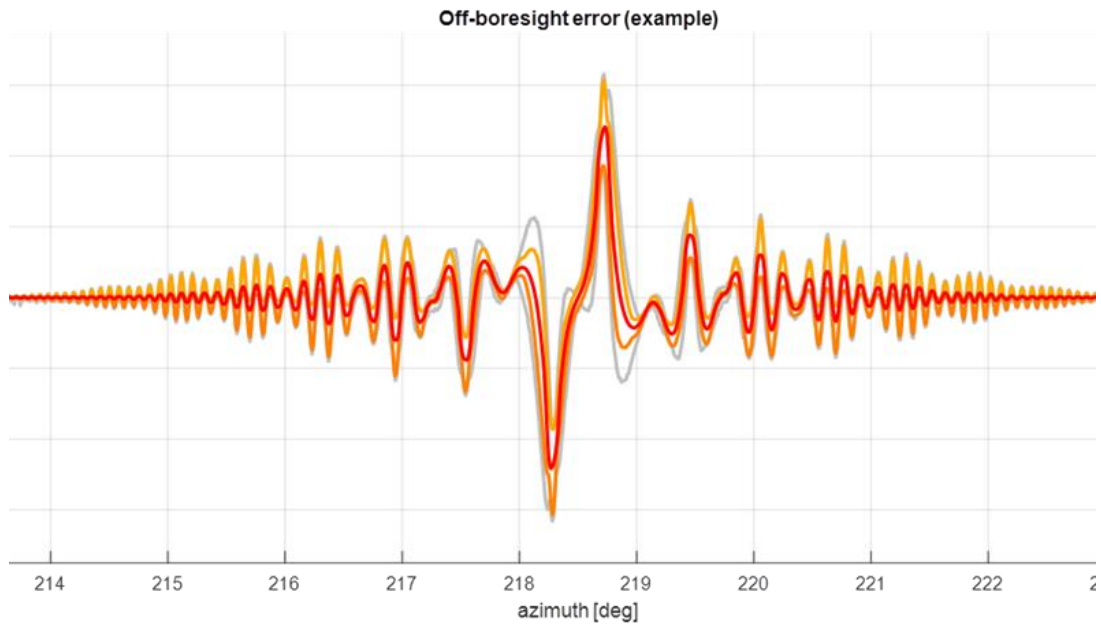


Figure 2.6 The off-boresight error for an infinite cylinder with a width of 25 m at a range of 3 km from the radar antenna. The error is point symmetrical around the azimuth angle to the obstacle.

## 3 Specific Input Parameters

### 3.1 Wind turbines

A DEA has been carried out for the newly planned Knockshanvo windfarm comprising nine wind turbines. All already consented wind turbines near the newly planned wind turbines are also taken into account. An overview of the situation is provided in Figure 3.1. The purple dots indicate the wind turbines under investigation and the cyan dots are the already consented wind turbines near the newly planned windfarm. The distance between the secondary radar at Woodcock Hill and the closest wind turbine of the newly planned windfarm measures approximately 5.9 km. There is a second newly planned windfarm called Oatfield, comprising eleven wind turbines with overlapping positions, indicated by yellow dots. Due to this a second DEA has been executed for the combined situation.

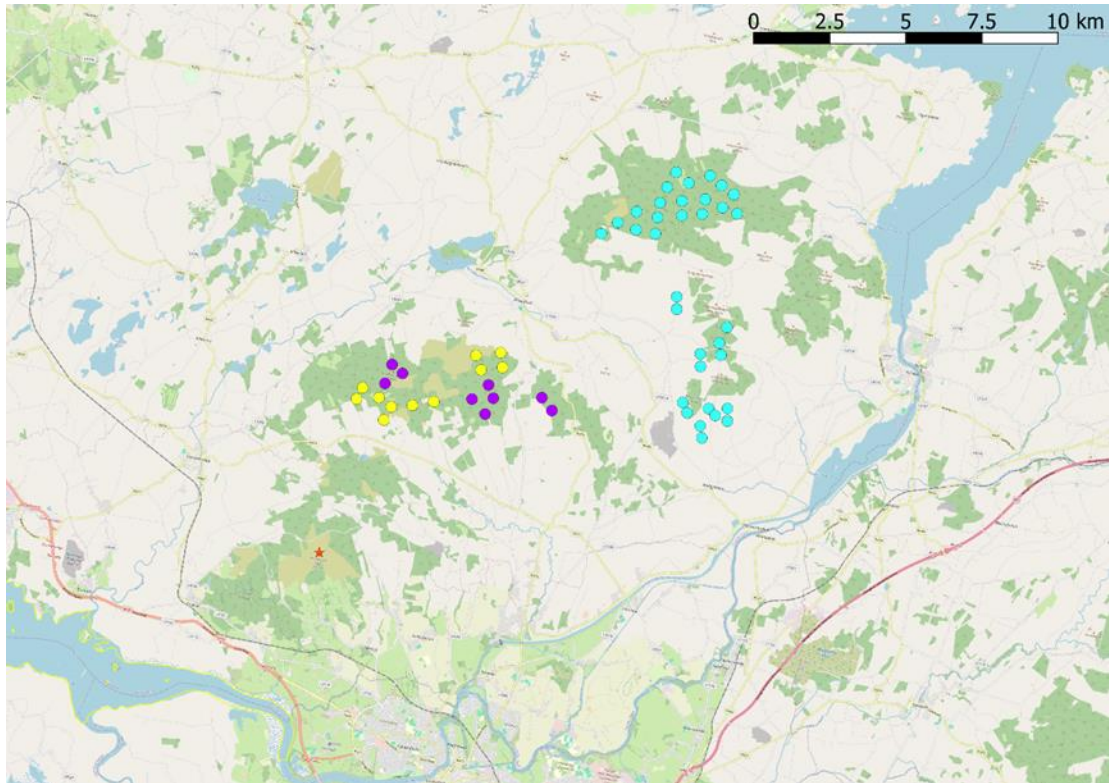


Figure 3.1 The locations of the newly planned windfarm Knockshanvo (purple dots) and Oatfield (yellow dots). The cyan dots correspond to the consented wind turbines near the newly planned wind turbines that are considered in this study. The secondary radar at Woodcock Hill is indicated by the red star. Image taken from OpenStreetMap.

In Table 3.1 an overview is presented of the positions, types, hub and tip heights of the already consented wind turbines near the newly planned wind turbines. The positions, type of the wind turbines and tip height have been received from Ai Bridges.

Table 3.1 Overview of the positions, type and tip heights of the already consented wind turbines near the newly planned wind turbines which have been provide by Ai Bridges. The UTM 29 N coordinates have been derived from the WGS84 longitude, latitude coordinates.

Nr.	Name/Owner	ID	UTM29 N East [m]	UTM29N North [m]	Lat [°]	Lon [°]	Terrain [m]	Type	Hub [m]	Tip [m]
1	Carrownagowan WF	Car-01	526768	5853389	52.82960	-8.60269	247	N133 4.8MW	101	167.5
2	Carrownagowan WF	Car-02	527227	5853851	52.83373	-8.59585	255	N133 4.8MW	101	167.5
3	Carrownagowan WF	Car-03	527862	5853738	52.83268	-8.58642	305	N133 4.8MW	101	167.5
4	Carrownagowan WF	Car-04	528515	5853736	52.83263	-8.57673	333	N133 4.8MW	101	167.5
5	Carrownagowan WF	Car-05	527764	5854322	52.83794	-8.58783	252	N133 4.8MW	101	167.5
6	Carrownagowan WF	Car-06	528480	5854275	52.83748	-8.57721	259	N133 4.8MW	101	167.5
7	Carrownagowan WF	Car-07	529249	5854498	52.83944	-8.56578	253	N133 4.8MW	101	167.5
8	Carrownagowan WF	Car-08	529898	5854673	52.84098	-8.55612	324	N133 4.8MW	101	167.5
9	Carrownagowan WF	Car-09	528462	5854766	52.84189	-8.57743	237	N133 4.8MW	101	167.5
10	Carrownagowan WF	Car-10	529161	5854962	52.84362	-8.56704	243	N133 4.8MW	101	167.5
11	Carrownagowan WF	Car-11	529897	5855166	52.84541	-8.55609	284	N133 4.8MW	101	167.5
12	Carrownagowan WF	Car-12	530509	5855012	52.84399	-8.54702	317	N133 4.8MW	101	167.5
13	Carrownagowan WF	Car-13	531012	5854915	52.84309	-8.53957	321	N133 4.8MW	101	167.5
14	Carrownagowan WF	Car-14	530784	5855511	52.84846	-8.54289	317	N133 4.8MW	101	167.5
15	Carrownagowan WF	Car-15	530333	5855722	52.85038	-8.54958	286	N133 4.8MW	101	167.5
16	Carrownagowan WF	Car-16	529903	5855961	52.85255	-8.55593	251	N133 4.8MW	101	167.5
17	Carrownagowan WF	Car-17	529256	5855590	52.84925	-8.56558	222	N133 4.8MW	101	167.5
18	Carrownagowan WF	Car-18	528590	5855311	52.84679	-8.57548	208	N133 4.8MW	101	167.5
19	Carrownagowan WF	Car-19	528784	5855853	52.85165	-8.57256	189	N133 4.8MW	101	167.5
20	Fahy Beg	FaB-01	530492	5848480	52.78527	-8.54788	118	N133 4.8MW	110	176.5

21	Fahy Beg	FaB-02	530702	5848181	52.78257	-8.54479	142	N133 4.8MW	110	176.5
22	Fahy Beg	FaB-03	531368	5848452	52.78497	-8.53490	213	N133 4.8MW	110	176.5
23	Fahy Beg	FaB-04	531213	5847838	52.77946	-8.53725	151	N133 4.8MW	110	176.5
24	Fahy Beg	FaB-05	531338	5847457	52.77603	-8.53543	124	N133 4.8MW	110	176.5
25	Fahy Beg	FaB-06	531627	5848272	52.78333	-8.53108	185	N133 4.8MW	110	176.5
26	Fahy Beg	FaB-07	531974	5848575	52.78604	-8.52590	194	N133 4.8MW	110	176.5
27	Fahy Beg	FaB-08	532052	5848173	52.78242	-8.52478	154	N133 4.8MW	110	176.5
28	Lackareagh Wind Farm	Lac-01	529612	5851842	52.81555	-8.56063	225	V150 6MW	105	180
29	Lackareagh Wind Farm	Lac-02	529693	5851443	52.81196	-8.55946	183	V150 6MW	105	180
30	Lackareagh Wind Farm	Lac-03	531429	5851185	52.80953	-8.53374	364	V150 6MW	105	180
31	Lackareagh Wind Farm	Lac-04	531286	5850631	52.80456	-8.53590	287	V150 6MW	105	180
32	Lackareagh Wind Farm	Lac-05	531416	5850253	52.80116	-8.53401	305	V150 6MW	105	180
33	Lackareagh Wind Farm	Lac-06	530743	5850160	52.80036	-8.54401	203	V150 6MW	105	180
34	Lackareagh Wind Farm	Lac-07	530835	5849753	52.79670	-8.54267	204	V150 6MW	105	180

For the DEA of the secondary radar the dimensions of the mast, nacelle and turbine blades need to be known. The dimensions used within the simulations of the newly planned turbines have been derived from 3D CAD drawings of the turbines that are available in the TNO wind turbine dimension database. The length of the nacelle is defined as the distance from the 'hub' to the back of the nacelle. The width of the nacelle has been derived from the effective surface area of the front of the nacelle and could deviate slightly from the actual dimensions. The widths of the blades have been derived from the frontal area of the blade. The dimensions of the existing and authorised wind turbines are presented in Table 3.2.

Table 3.2 The dimensions of the consented wind turbines in the neighbourhood.

Wind Turbine Type	Manufacturer	Mast Length [m]	Mast ø top [m]	Mast ø base [m]	Nacelle Height [m]	Nacelle Width [m]	Nacelle Length [m]	Blade Length [m]	Blade Width [m]
N133@167.5	Nordex	98.9	3.3	4.3	4.7	5.1	16.3	66.5	3.7
N133@176.5	Nordex	107.9	3.3	4.3	4.7	5.1	16.3	66.5	3.7
V150EnVentus@180	Vestas	101.9	4.0	4.2	5.5	8.6	21.6	74.6	3.4

The position and dimensions of all newly planned wind turbines are presented in Figure 3.2 and in Table 3.3. The coordinates of the wind turbines are given in WGS84 coordinates and have been received from Ai Bridges. The UTM 29N coordinates have been derived from the WGS84 coordinates. The height of the ground level at the locations is given with respect to the EGM96 geoid and has been derived from the SRTM1 terrain height database. Due to the fact that the positions of a second newly planned windfarm Oatfield, comprising eleven wind turbines, overlap with those of Knockshanvo, the combined situation of both wind farm will also be considered in the report.

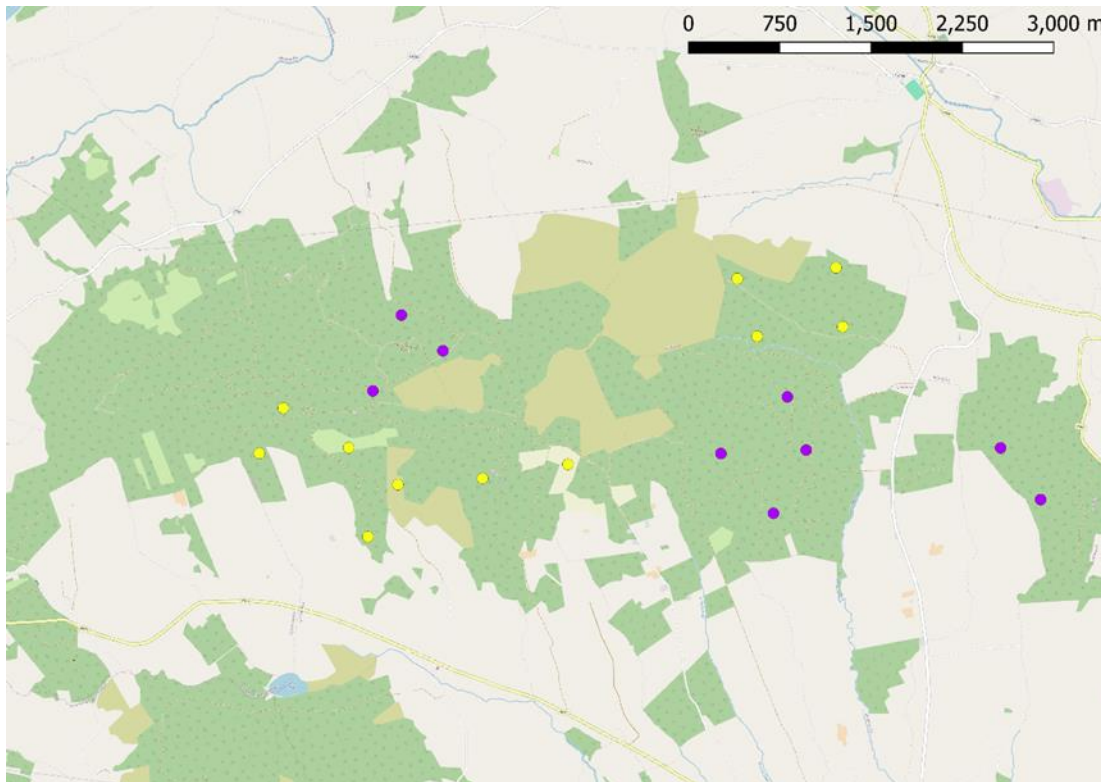


Figure 3.2 The nine newly planned wind turbines of Knockshanvo windfarm (purple dots) and the eleven nearby turbines of Oatfield windfarm (yellow dots) both under investigation. Image taken using OpenStreetMap.

Table 3.3 Overview of the positions and tip heights newly planned wind turbines of the Knockshanvo windfarm and Oatfield windfarm. The WGS84 Latitude and longitude coordinates and tip heights have been provided by Ai Bridges. The UTM 29N coordinates has been derived from these.

Location	ID	UTM29 N East [m]	UTM29 N North [m]	Lat [°]	Lon [°]	Terrain [m]	Tip Height AGL [m]
Knockshanvo	Kno-01	520777	5847152	52.77380	-8.69201	265	185
	Kno-02	520884	5847809	52.77970	-8.69039	241	185
	Kno-03	521277	5847590	52.77771	-8.68458	265	185
	Kno-04	523682	5847216	52.77425	-8.64895	219	185
	Kno-05	524125	5847779	52.77930	-8.64234	192	185
	Kno-06	524363	5847383	52.77572	-8.63884	176	185
	Kno-07	524202	5846822	52.77068	-8.64127	176	185
	Kno-08	525925	5847717	52.77865	-8.61565	187	185

	Kno-09	526331	5847366	52.77548	-8.60966	196	185
Oatfield	Oat-01	519963	5846466	52.76766	-8.70412	247	180
	Oat-02	520674	5846657	52.76935	-8.69357	242	180
	Oat-03	520974	5845972	52.76318	-8.68917	180	180
	Oat-04	521131	5846440	52.76738	-8.68681	217	180
	Oat-05	521803	5846627	52.76904	-8.67684	208	180
	Oat-06	524307	5848897	52.78934	-8.63956	186	180
	Oat-07	524457	5848435	52.78517	-8.63737	193	180
	Oat-08	523530	5848649	52.78714	-8.65110	223	180
	Oat-09	523783	5848217	52.78325	-8.64738	193	180
	Oat-10	522467	5846879	52.77128	-8.66698	231	180
	Oat-11	520084	5846870	52.77128	-8.70231	260	180

The dimensions of the newly planned wind turbines are based on the Nordex N149 Delta 4000 with a tip height of 185 m for Knockshanvo windfarm and the for Oatfield the Vestas V150 EnVentus with a tip height of 180 m. The dimensions of these wind turbines used within the simulations are listed in Table 3.4.

Table 3.4 The dimension of the newly planned wind turbine of Knockshanvo and Oatfield windfarm used within the simulations.

Wind Turbine Type	Manufacturer	Mast Length [m]	Mast ø top [m]	Mast ø base [m]	Nacelle Height [m]	Nacelle Width [m]	Nacelle Length [m]	Blade Length [m]	Blade Width [m]
N149@185	Nordex	107.9	3.3	4.3	4.7	5.1	16.3	74.5	3.7
V150EnVentus@180	Vestas	101.9	4.0	4.2	5.5	8.6	21.6	74.6	3.4

## 3.2 Secondary Radar Woodcock Hill

The radar at Woodcock Hill is an en-route stand-alone Mode-S MSSR, see Figure 3.3. The main parameters, coordinates and antenna height have been received from Ai Bridges Limited [3]. The radar parameters that are relevant for this study are presented in Table 3.5.



Figure 3.3 The stand-alone en-route Mode-S MSSR at Woodcock Hill housed in a radome (Image source: IAA).

Table 3.5 Relevant radar parameters of the stand-alone Mode-S MSSR at Woodcock Hill [3].

Parameter	Value
Antenna position	Stand-alone
X (UTM29N)	519760 E
Y (UTM29N)	5841280 N
Latitude (WGS84)	52.721047° N
Longitude (WGS84)	8.707439° W
Height (EGM96)	10 m AGL
	307.8 m AMSL
Number of elements	35 m
Antenna length	8.5 m
Frequency	1090 MHz
Maximum Instrumented Range	256 NM

# 4 DEA of the MSSR at Woodcock Hill

In this section we determine the effect the presence of wind turbines can have on the performance of the stand-alone MSSR at Woodcock Hill. In order to do this, we first carry out the so-called Line-of-Sight (LoS) analysis for the MSSR. This analysis will give insight into the visibility of the wind farm as seen from the MSSR's position. In addition to the LoS analysis we also calculate the off-boresight error (OBE) the wind farm causes on the bearing measurements of the secondary radar.

Three situations have been assessed in this DEA. The first situation only concerns the presence of already consented wind turbines and within the second situation the newly planned wind turbines at Knockshanvo are included, Finally in the third situation the newly planned wind turbines at Oatfield are included as well. An overview of the considered wind turbines is provided by Figure 4.1, similar to Figure 3.1. For the MSSR study only the wind turbines that are located nearby the sector of  $\pm 2^\circ$  around the newly planned wind turbines (red dotted lines) need to be considered. However, for a complete analysis on the effects of the newly planned wind turbines, all consented wind turbines indicated mentioned in Section 3.1 are taken into account.

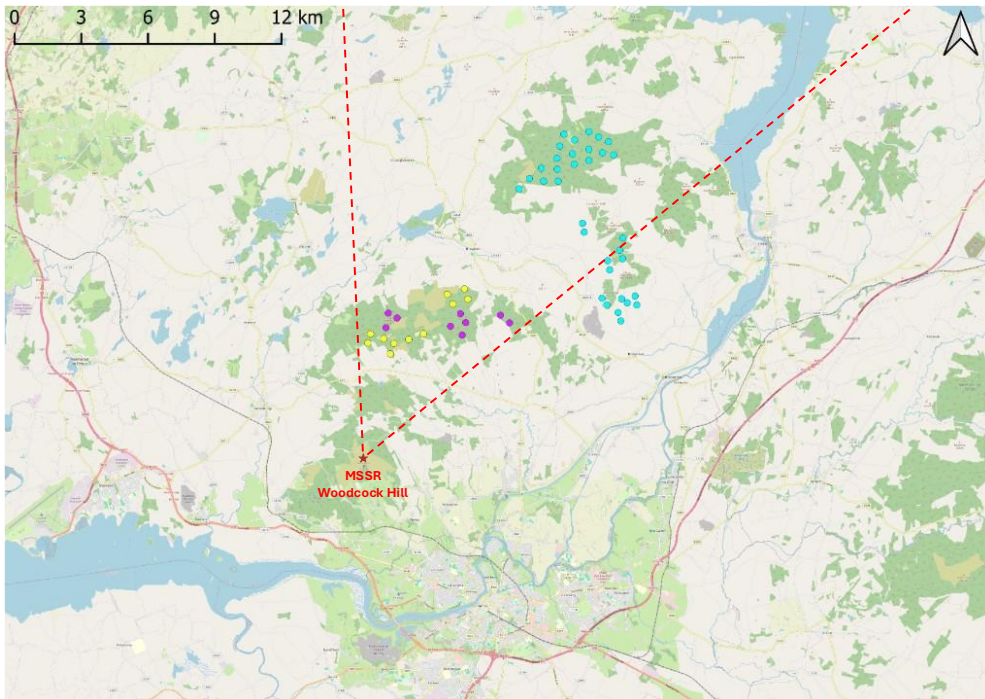


Figure 4.1 The locations of the newly planned windfarm Knockshanvo (purple dots) and Oatfield (yellow dots). The cyan dots correspond to the consented wind turbines near the newly planned wind turbines that are considered in this study. The secondary radar at Woodcock Hill is indicated by the red star. Image taken from OpenStreetMap.

In order to perform the Line-of-Sight analysis, a Digital Elevation Model (DEM) is required. The terrain altitude data in the DEM is taken from the Shuttle Radar Topography Mission (SRTM) database that has a resolution of approximately 25 meter. In Figure 4.2 an overview of the terrain altitude is shown. As can be observed, the terrain is a bit hilly. The radar location is shown, as well as the locations of the other existing and the planned wind turbines.

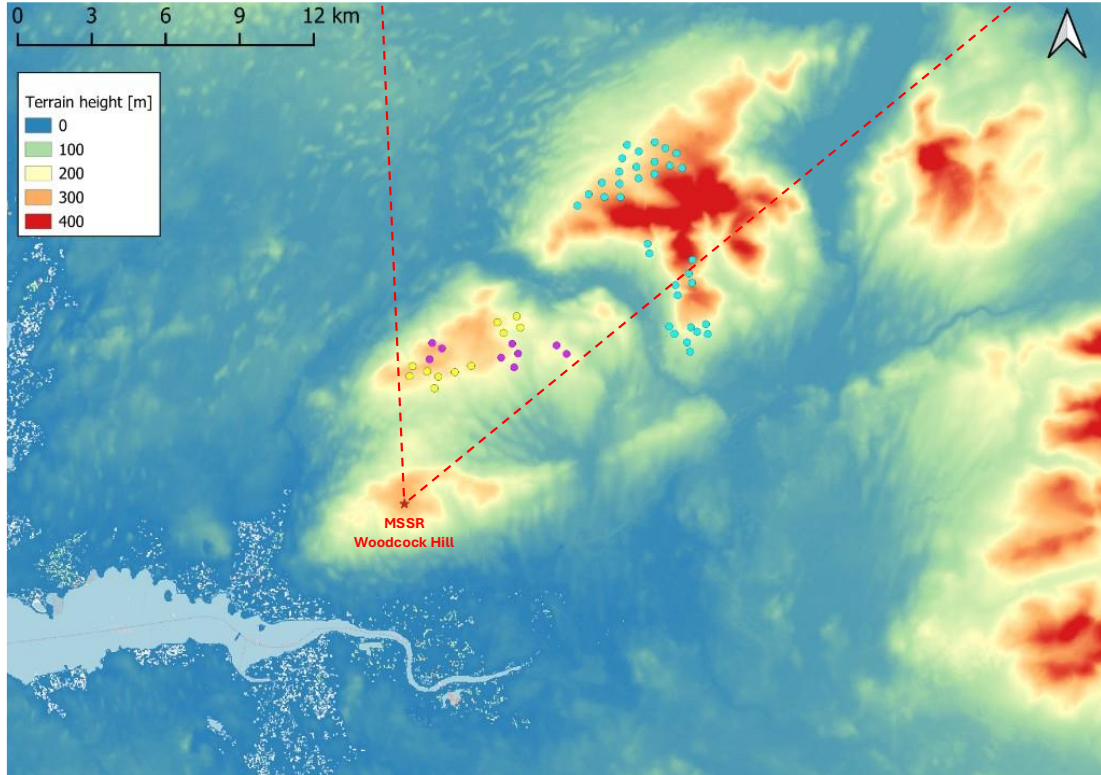


Figure 4.2 Height map around the newly planned wind turbines (yellow and purple dots) showing the MSSR at Woodcock Hill (red star), and the consented wind turbines (cyan dots).

## 4.1 Radar horizon

In this section we show the extent of the wind farm in azimuth and elevation for the MSSR. These results reveal whether the wind farm has impact on the radar horizon. A wind turbine influences the radar horizon when the elevation angle to the tip height of the wind turbine is larger than the elevation angle to all other objects at the same azimuth angle, extending all the way up to the instrumented range of the MSSR, which measures 256 NM. Given the elevation angle to the tip height, aircraft at different altitudes are influenced at different ranges as shown in Figure 4.3. Here, the elevation angle to the tip height of the wind turbine is indicated by a grey line. The MSSR replies of aircraft above this line are not influenced by the wind turbine. Aircraft replies below the line may be influenced by the wind turbine.

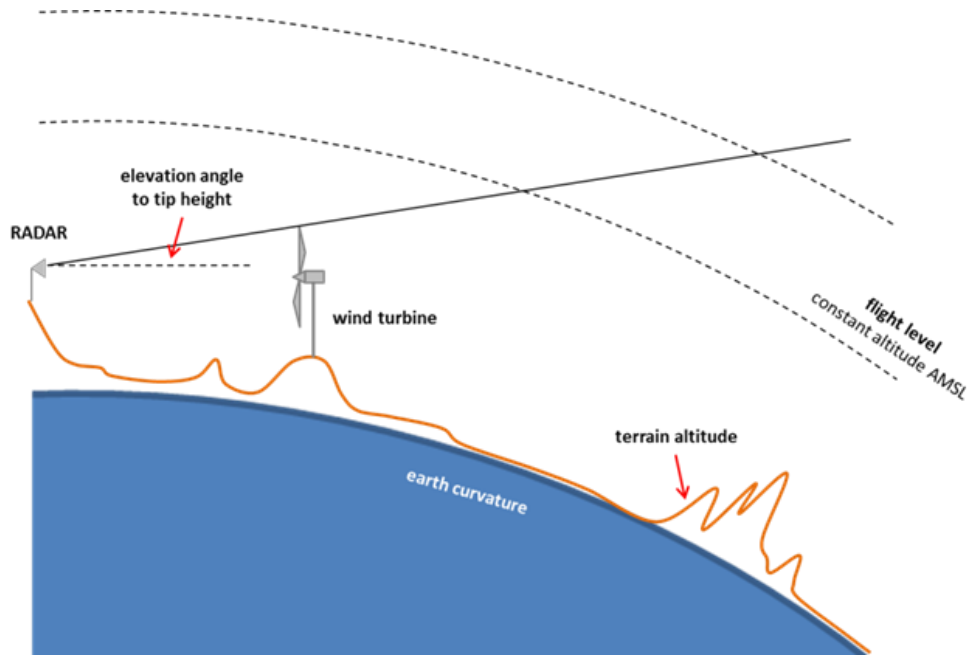


Figure 4.3 Overview of the overall Line-of-Sight geometry at fixed azimuth.

Note that this LoS analysis takes into account both the curvature of the Earth as well as the shape of the terrain. Electromagnetic waves do not follow straight lines, but tend to curve along the surface of the Earth to some extent as the refractivity index of the air varies with altitude. These refraction effects are generally taken into account by multiplying the radius of the Earth by a so-called  $k$ -factor. A common value for the  $k$ -factor is 1.33, which has been used in all results. By using the  $k$ -factor, we can treat the radio waves as if travelling along straight lines instead of curved lines.

In the next figure we show azimuth-elevation plots of the surrounding terrain (the radar horizon) including the wind farm. An orange (new) or green (existing and authorised) line indicates the wind turbine up to the tip height. The horizontal red lines indicate the blades of the wind turbine at hub height. Note that the scaling of the horizontal and vertical axes in these figures is different. This means that the wind turbines appear high and narrow. The width of the blades in the horizontal direction (azimuth) is in fact the actual width of the wind turbine as seen from the radar.

As can be seen in Figure 4.4 the radar has Line-of-Sight to the consented wind turbines as well as the newly planned wind turbines at Knockshanvo. The new turbines are planned at approximately 10° to 48° in azimuth with respect to the North as seen from the radar's location. A similar figure is shown for the scenario where the wind farm of Oatfield is included as well, visualized by the added planned wind turbines. This results in an increase of the azimuth sector from approximately 2° to 48° with respect to the North. As mentioned earlier, for the MSSR study only the wind turbines that are located nearby the sector of ±2° around the newly planned wind turbines need to be considered. Nevertheless, for completeness, all already existing wind turbines as shown in the figures below are taken into account.

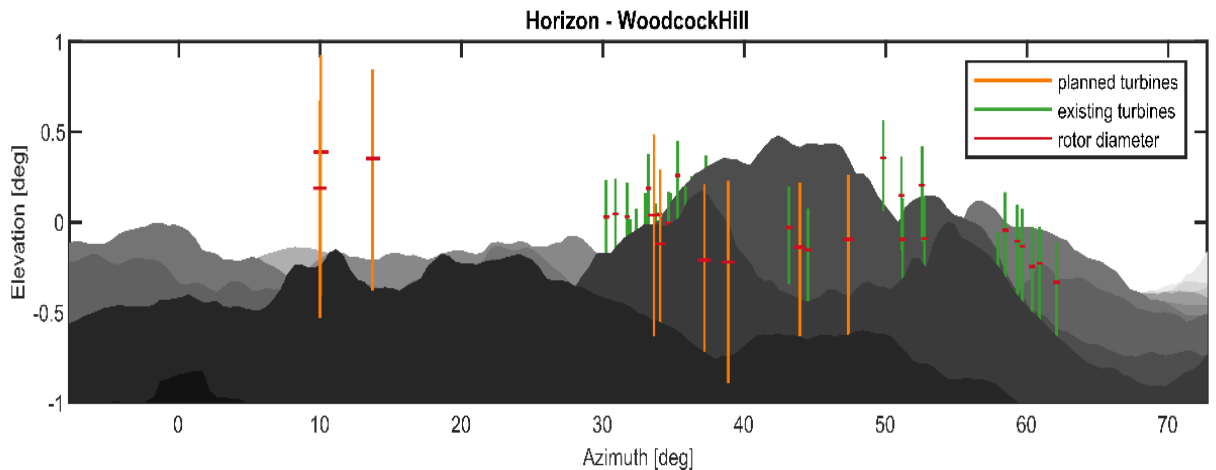


Figure 4.4 Horizon of the consented wind turbines as well as the newly planned wind turbines at Knockshanvo as seen from the MSSR.

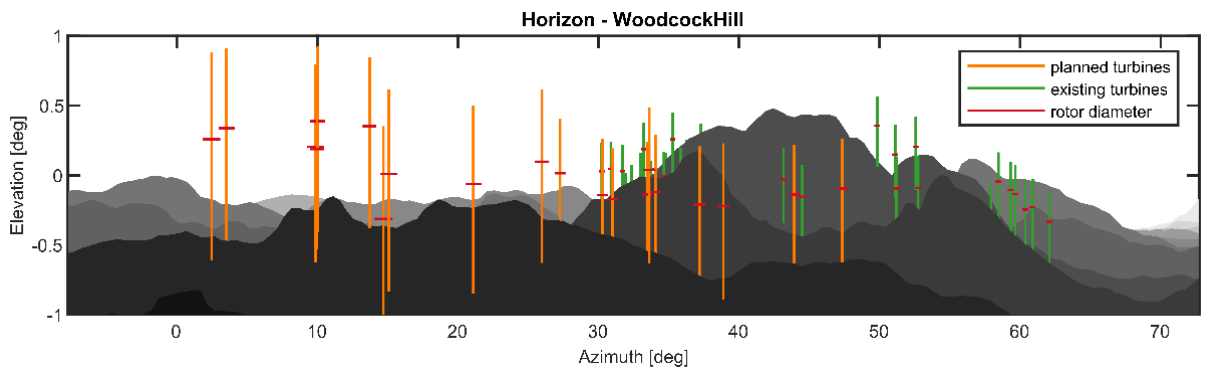


Figure 4.5 Horizon of the consented wind turbines as well as the newly planned wind turbines at Knockshanvo as well as the newly planned wind turbines at Oatfield as seen from the MSSR.

## 4.2 Line-of-Sight to individual wind turbines

Next, we take a look at the Line-of-Sight to the individual wind turbines as seen from the MSSR. From these figures we can draw conclusions on aircraft ranges and altitudes at which the wind turbine potentially interferes with MSSR operations.

The red line in each figure represents 0 m AMSL. The black line above the red line shows the terrain altitude along the azimuth line towards the wind turbine. The radar is indicated by a red triangle on the left of each figure. The wind turbine is drawn at its corresponding range in each figure. The first Fresnel zone towards the tip and hub heights of the wind turbine are drawn as dashed red and blue ellipsoids, respectively.

A dashed black line passes through the point on the ground with the largest elevation angle as seen from the radar antenna. This is the point that determines the radar horizon in absence of the wind turbine. Furthermore, a red and orange zone are drawn. When orange and red zones are visible, the radar horizon is diminished by the wind turbine. The red zone indicates the reduction of the radar horizon due to the blades of the wind turbine. The orange zone indicates the reduction of the radar horizon by the mast of the wind turbine. In each figure, flight levels at 5000 ft, 7000 ft and 10000 ft are shown as well.

Note that in the red and orange areas the radar is not completely 'blind'. The red and orange colours merely indicate where impact of the wind turbines on the radar performance can potentially occur. In these regions the signal from a transponder towards the SSR antenna passes a wind turbine. This means that the wave front of the signal transmitted by the transponder will be disturbed by the wind turbine and does not necessarily mean that the impact on the position estimation of the target by the MSSR is significant. The error in the position estimation due to wind turbines placed in the signal path is further investigated in Section 4.4.

Figure 4.6 and Figure 4.7 show the Line-of-Sight as seen from the MSSR towards a newly planned wind turbine at Knockshanvo. As can be seen, the radar has Line-of-Sight towards the wind turbine. At a range of 100 km, at the azimuth angle towards the wind turbine, a target below approx. 10140 ft might be obscured by the wind turbine (red and orange zones) and above that altitude the radar looks over the tip height of the turbine and the signal will not be obscured. For a target below approximately 2345 ft the radar signal will be behind the hills or horizon anyway.

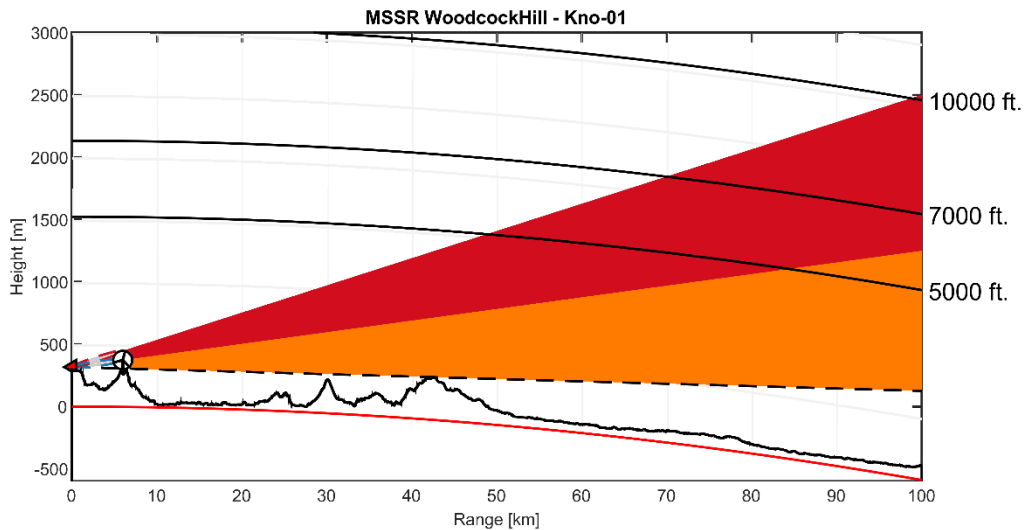


Figure 4.6 Line-of-Sight towards planned turbine Kno-01 as seen from the MSSR.

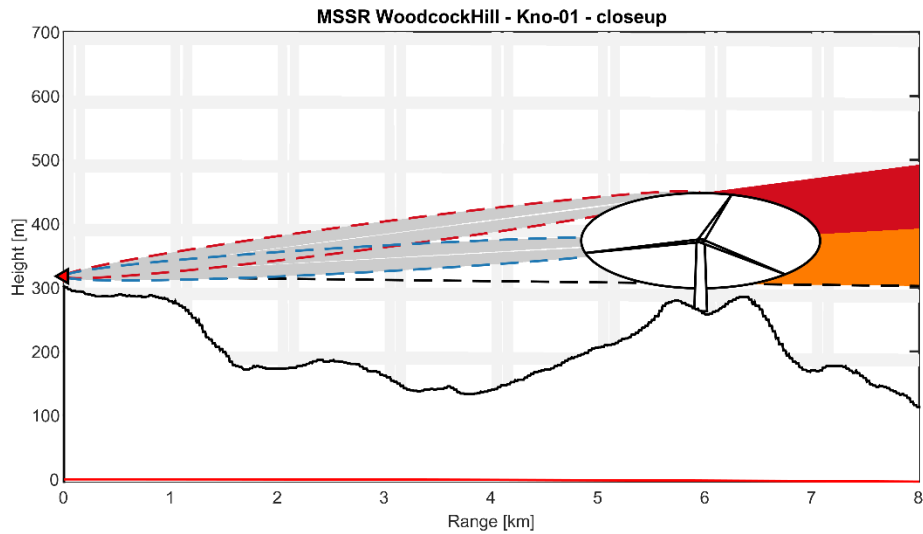


Figure 4.7 Closeup of Line-of-Sight towards planned turbine Kno-01 as seen from the MSSR.

It can be seen that the presence of the red and orange area are significant, which is due to the close distance of the wind turbine to the radar. For most of the other newly planned wind turbines at Knockshanvo, the results are similar. Some exceptions arise due to the location of the wind turbine and the terrain height in that particular azimuth direction, resulting in a smaller region of aircraft ranges and altitudes at which the wind turbine potentially interferes. Figure 4.8 and Figure 4.9 show the Line-of-Sight plot, and a close-up, of such an example wind turbine Kno-05, respectively. Similar, as can be seen, the radar has Line-of-Sight towards the wind turbine. Here, at a range of 100 km, at the azimuth angle towards the wind turbine, a target below approx. 5307 ft might be obscured by the wind turbine (red and orange zones) and above that altitude the radar looks over the tip height of the turbine and the signal will not be obscured. For a target below approximately 3511 ft the radar signal will be behind the hills or horizon anyway.

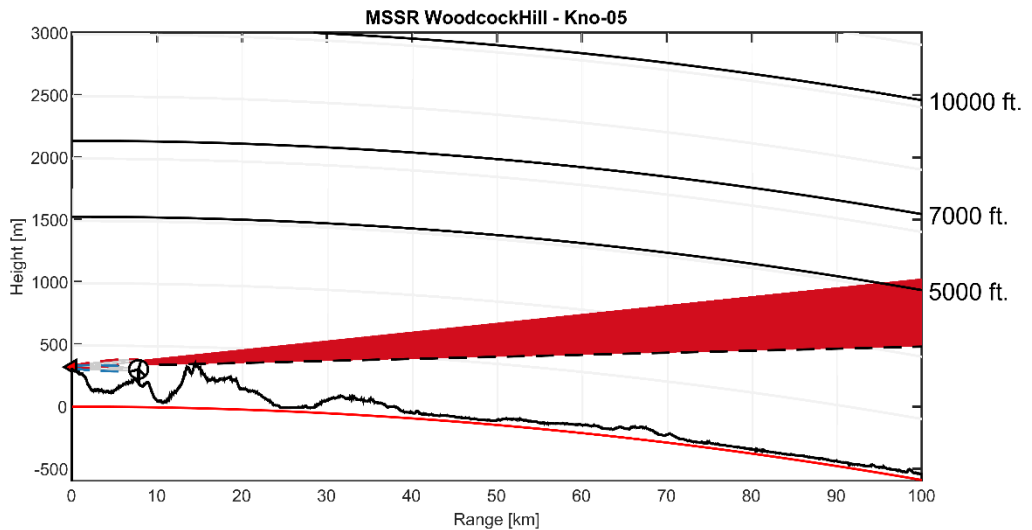


Figure 4.8 Line-of-Sight towards planned turbine Kno-05 as seen from the MSSR.

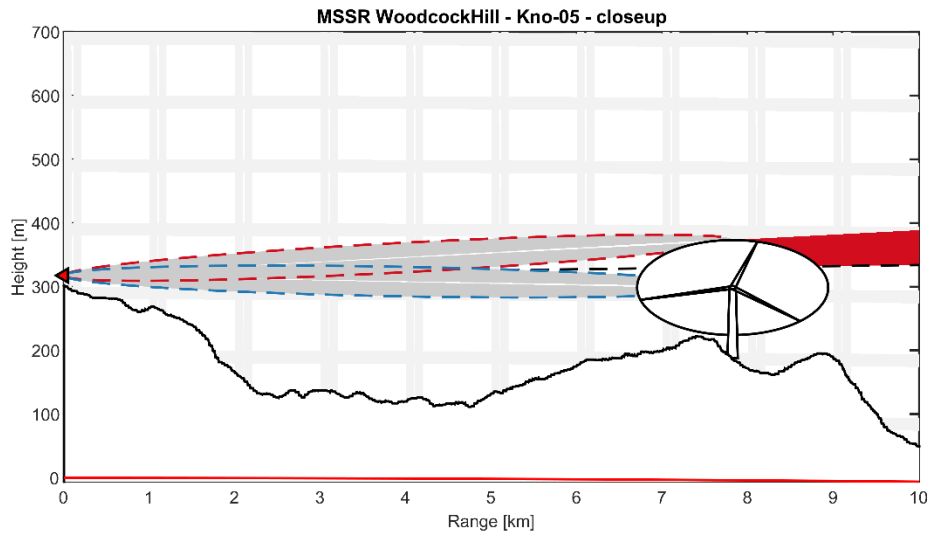


Figure 4.9 Closeup of Line-of-Sight towards planned turbine Kno-05 as seen from the MSSR.

For all of the newly planned wind turbines at wind farm Oatfield similar observations as above can be done.

Moreover, some of the wind turbines at Knockshanvo are located in between the radar system and a hill that obscures the Line-of-Sight of an aircraft at certain altitudes. In these cases, of which an example of Kno-06 is shown in Figure 4.10 and Figure 4.11, the aircraft is either behind this hill (i.e., below the dotted line) or is in direct Line-of-Sight of the radar without potential interference of the planned wind turbine (i.e., above the dotted line). Here, at a range of 100 km, at the azimuth angle towards the wind turbine, a target below approximately 5581 ft the radar signal will be behind the hills, and above this altitude will not be affected by the wind turbine. Such situation is not applicable to any of the wind turbines at wind farm Oatfield.

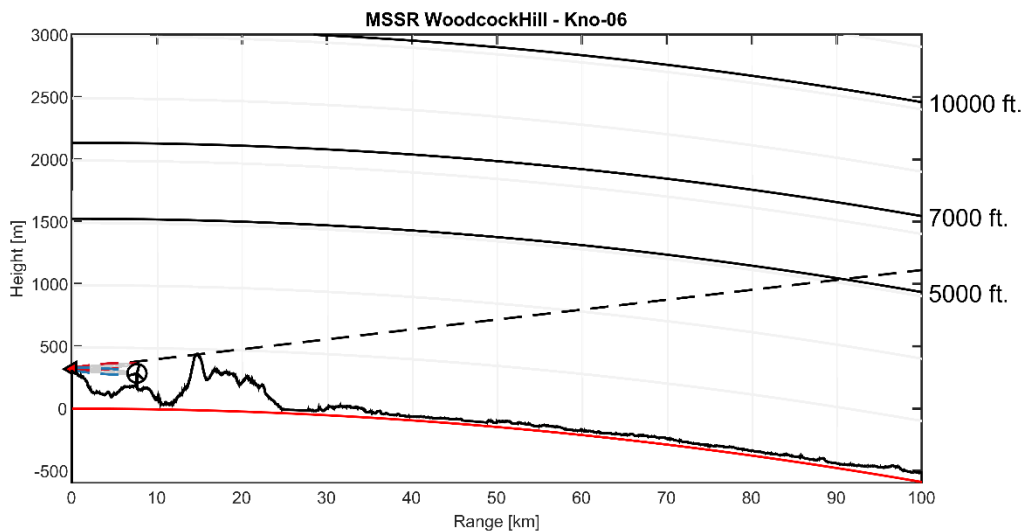


Figure 4.10 Line-of-Sight towards planned turbine Kno-06 as seen from the MSSR.

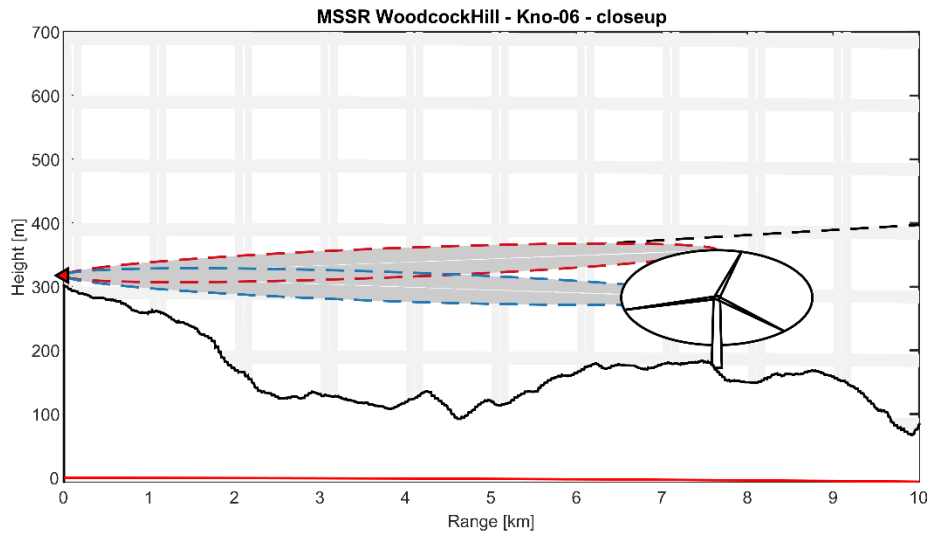


Figure 4.11 Closeup of Line-of-Sight towards planned turbine Kno-06 as seen from the MSSR.

Although not all consented wind turbines are within the sector of  $\pm 2^\circ$  around the newly planned wind turbines as seen from the MSSR, for completeness, the results of the Line-of-Sight analysis to all wind turbines are summarized in the table below.

Table 4.1 Summary of heights at 100 km ground range where the wind turbine might influence the MSSR performance.

Nr.	Name	Unobscured Height [ft]	Obscured Height [ft]
1	Car-01	1868	4974
2	Car-02	2229	5044
3	Car-03	3105	6107
4	Car-04	4576	6622
5	Car-05	2723	4862
6	Car-06	3486	4953
7	Car-07	4902	4733
8	Car-08	5619	6047
9	Car-09	3061	4439
10	Car-10	4094	4488
11	Car-11	5226	5197
12	Car-12	5918	5778
13	Car-13	5591	5805
14	Car-14	5756	5669
15	Car-15	5276	5119
16	Car-16	4209	4483
17	Car-17	3284	4014
18	Car-18	2938	3797
19	Car-19	2819	3385

20	FaB-01	4276	2132
21	FaB-02	3332	2742
22	FaB-03	3152	4439
23	FaB-04	3040	2961
24	FaB-05	2599	2288
25	FaB-06	3152	3752
26	FaB-07	3128	3918
27	FaB-08	2944	2999
28	Lac-01	6436	4679
29	Lac-02	6542	3745
30	Lac-03	3596	7536
31	Lac-04	3880	5992
32	Lac-05	4342	6427
33	Lac-06	3899	4219
34	Lac-07	4398	4265
35	Kno-01	2345	10140
36	Kno-02	2362	8207
37	Kno-03	1795	9536
38	Kno-04	3238	6816
39	Kno-05	3511	5307
40	Kno-06	5581	4683
41	Kno-07	5885	4835
42	Kno-08	6442	4800
43	Kno-09	5156	5120
44	Oat-01	2008	9779
45	Oat-02	2385	9140
46	Oat-03	2055	5739
47	Oat-04	2132	7740
48	Oat-05	2096	6890
49	Oat-06	2327	4587
50	Oat-07	3168	4927
51	Oat-08	2759	6194
52	Oat-09	1829	5080
53	Oat-10	2410	7775
54	Oat-11	1893	10029

As can be observed from the diagrams and tables above, there is full line of sight between the radar and all the consented and newly planned wind turbines.

### 4.3 Line-of-Sight coverage

The results in the previous sections give insight to which extent the wind farm can potentially affect the bearing estimate provided by the MSSR. In this section we show the locations of the affected areas in the Line-of-Sight coverage diagrams. Coverage diagrams are shown for targets at altitudes of 5000, 7000, 10000 and 35000 ft for the existing situation and after the newly planned wind turbines has been built. A coverage diagram shows whether the performance of the secondary radar can be influenced by the target at a given altitude.

The affected azimuth sector of a single wind turbine is taken as 5° on both sides of the wind turbine, 10° in total. As discussed in Section 2.1 in more detail, outside this 5° sector the impact of the wind turbine on the bearing determination will be smaller than the MSSR bearing accuracy.

For each target height three scenarios are considered:

1. The coverage for the case when only the consented wind turbines are considered;
2. The coverage for the case when the planned wind turbines at Knockshanvo are added;
3. The coverage for the case when the planned wind turbines at both Knockshanvo and Oatfield are added.

By comparing these figures the effects of the newly planned turbines on the Line-of-Sight coverage can be determined.

The Line-of-Sight coverage diagrams for the MSSR at target heights of 5000, 7000, 10000 and 35000 ft are shown in the figures below. Areas affected by the mast up to the hub height of the wind turbines are shown in orange. Areas affected from hub height up to the tip height are shown in red. The radar is indicated by a red star, the yellow dots are the newly planned wind turbines and the blue dots are the consented wind turbines.

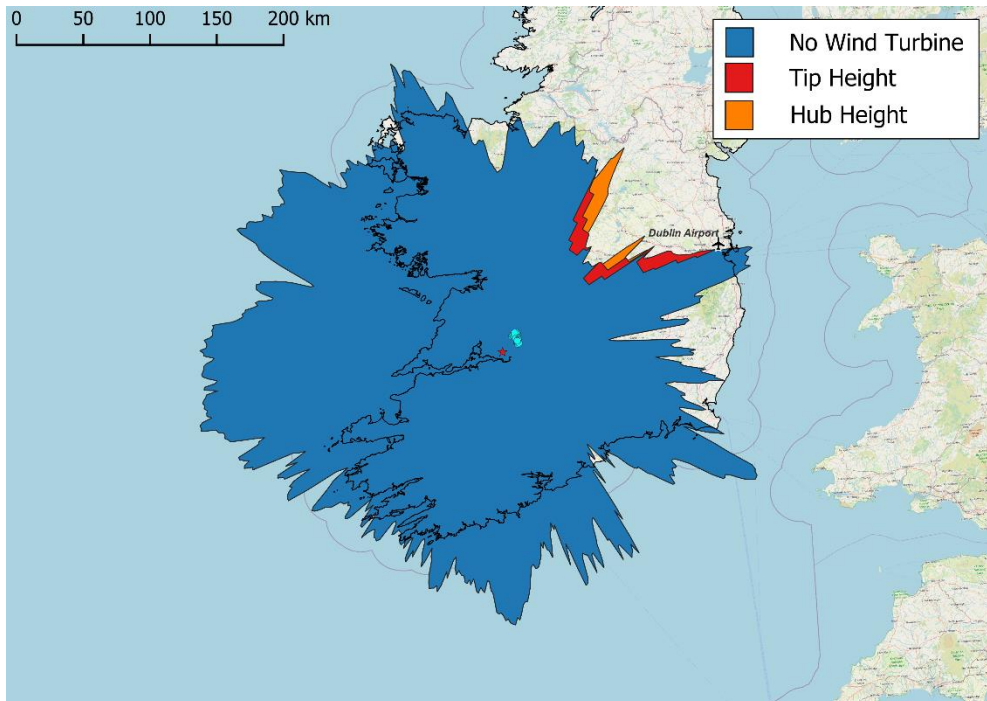


Figure 4.12 Line-of-Sight coverage diagram for a target at 5000 ft AMSL as seen from the MSSR. Only the consented wind turbines are taken into account.

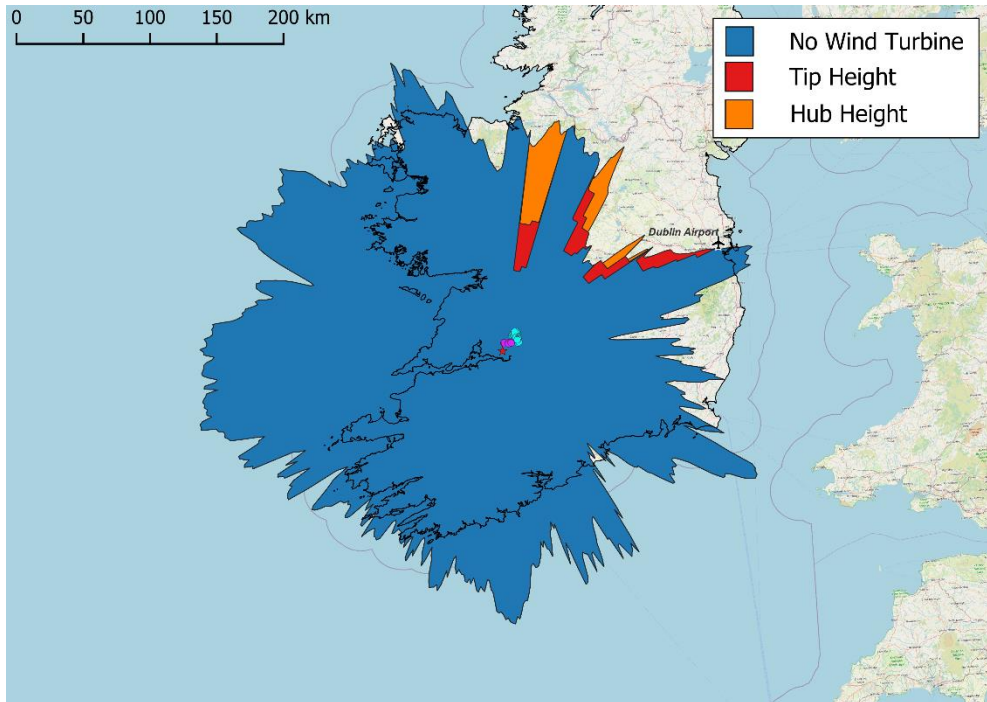


Figure 4.13 Line-of-Sight coverage diagram for a target at 5000 ft AMSL as seen from the MSSR. All consented wind turbines, and the newly planned wind turbines at Knockshanvo are taken into account.

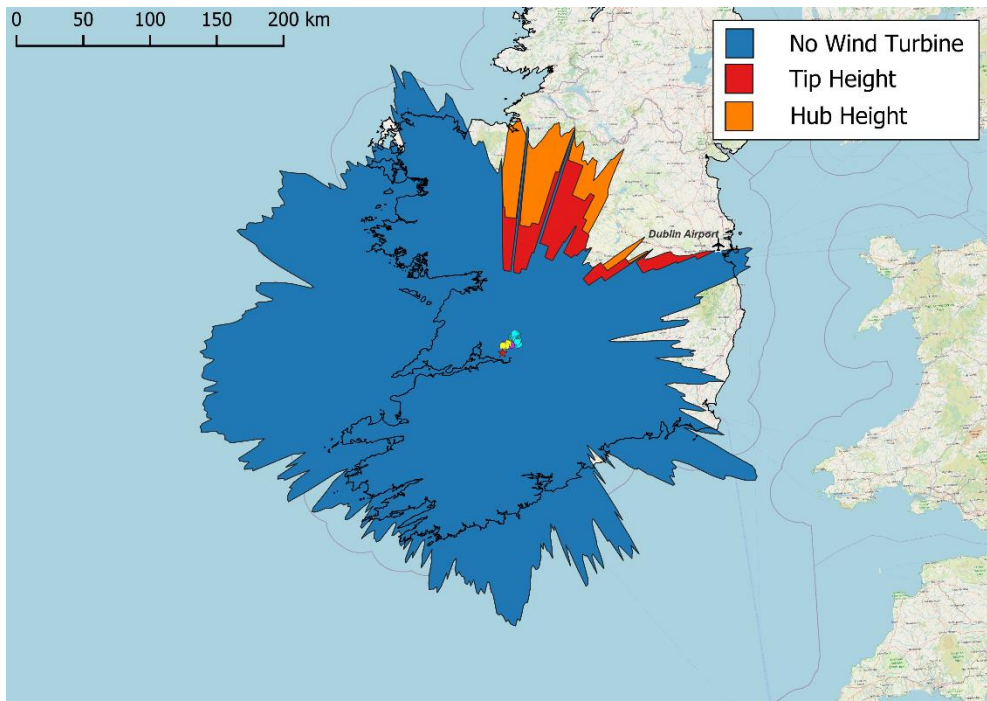


Figure 4.14 Line-of-Sight coverage diagram for a target at 5000 ft AMSL as seen from the MSSR. All consented wind turbines, and the newly planned wind turbines at Knockshanvo and Oatfield are taken into account.

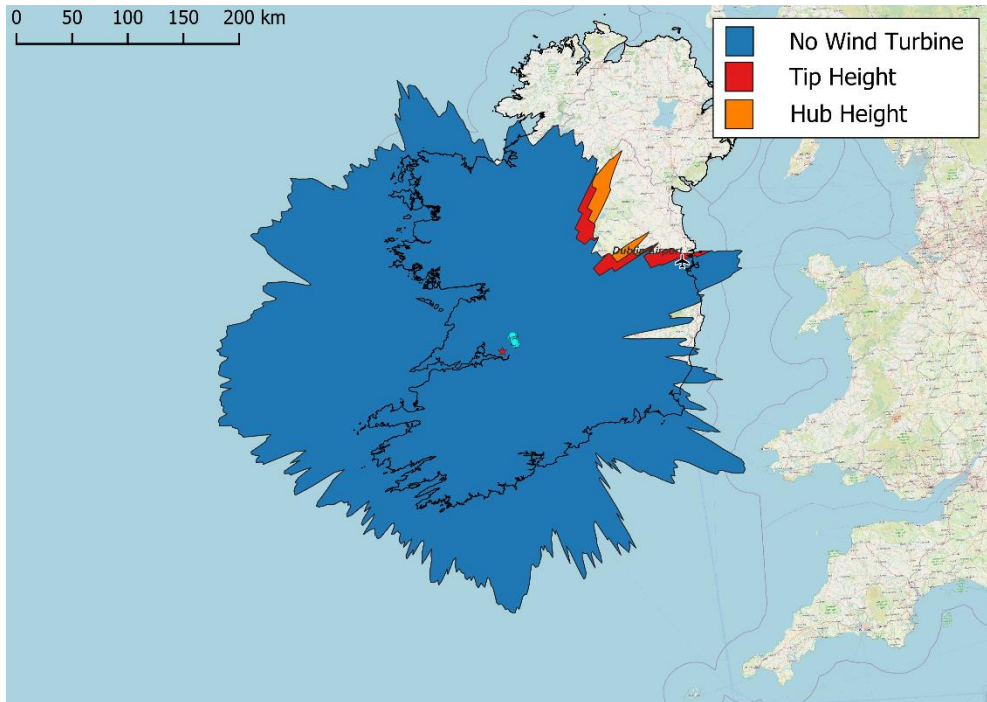


Figure 4.15 Line-of-Sight coverage diagram for a target at 7000 ft AMSL as seen from the MSSR. Only the consented wind turbines are taken into account.

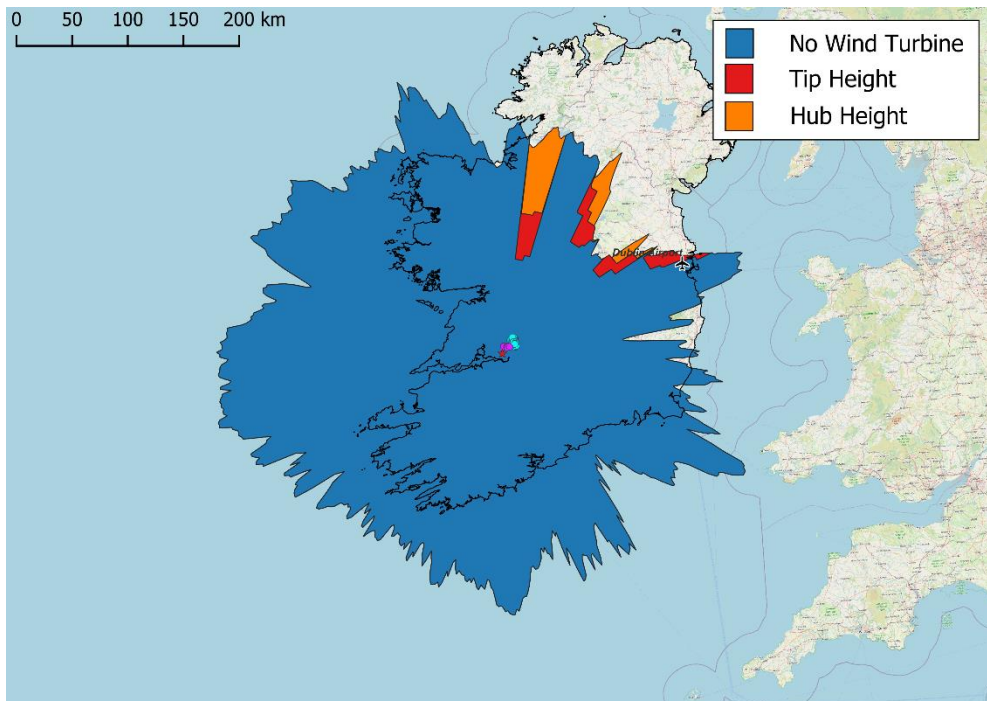


Figure 4.16 Line-of-Sight coverage diagram for a target at 7000 ft AMSL as seen from the MSSR. All consented wind turbines, and the newly planned wind turbines at Knockshanvo are taken into account.

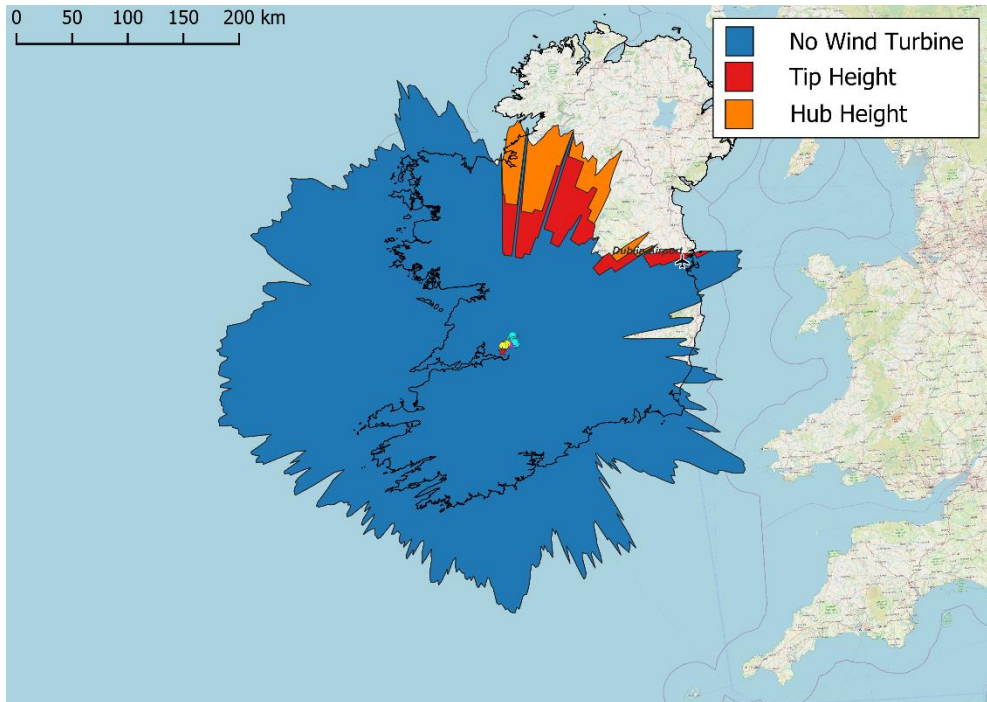


Figure 4.17 Line-of-Sight coverage diagram for a target at 7000 ft AMSL as seen from the MSSR. All consented wind turbines, and the newly planned wind turbines at Knockshanvo and Oatfield are taken into account.

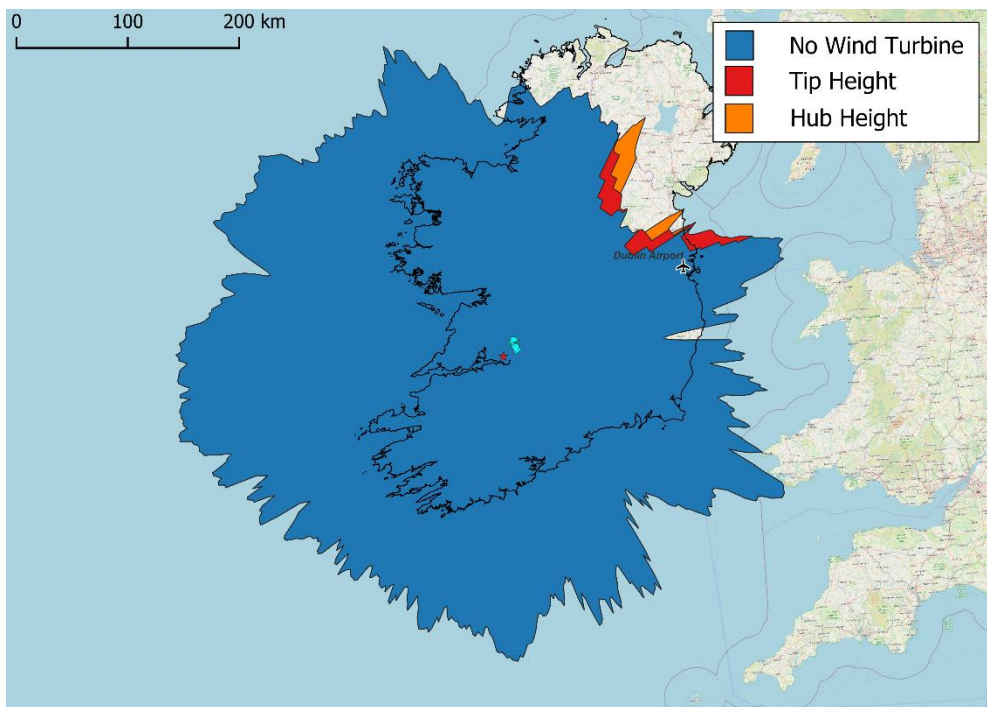


Figure 4.18 Line-of-Sight coverage diagram for a target at 10000 ft AMSL as seen from the MSSR. Only the consented wind turbines are taken into account.

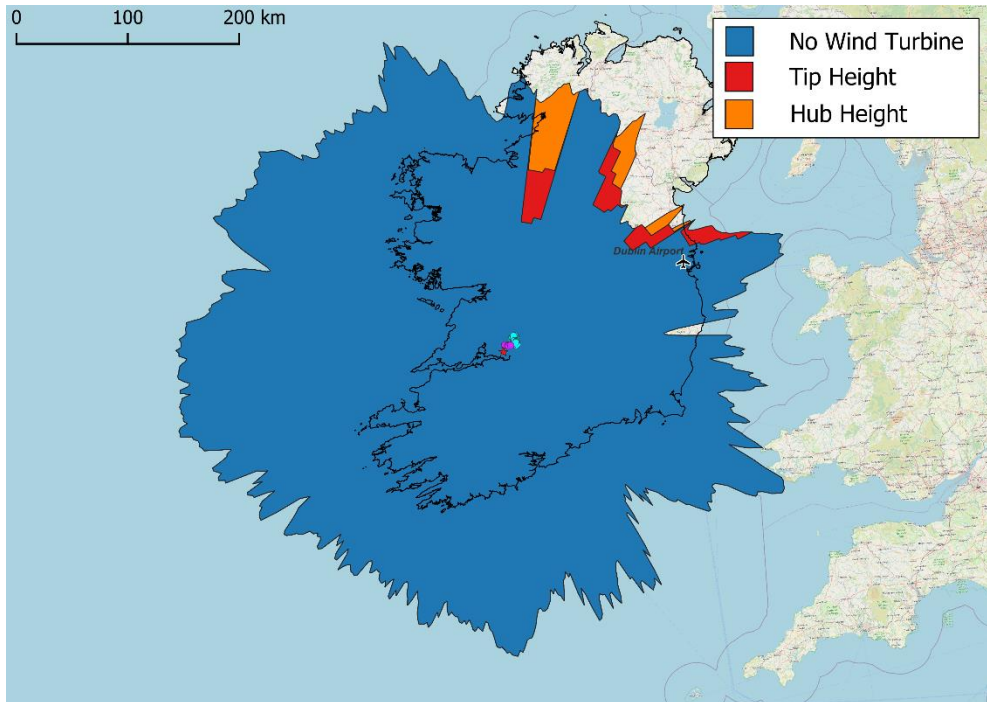


Figure 4.19 Line-of-Sight coverage diagram for a target at 10000 ft AMSL as seen from the MSSR. All consented wind turbines, and the newly planned wind turbines at Knockshanvo are taken into account.

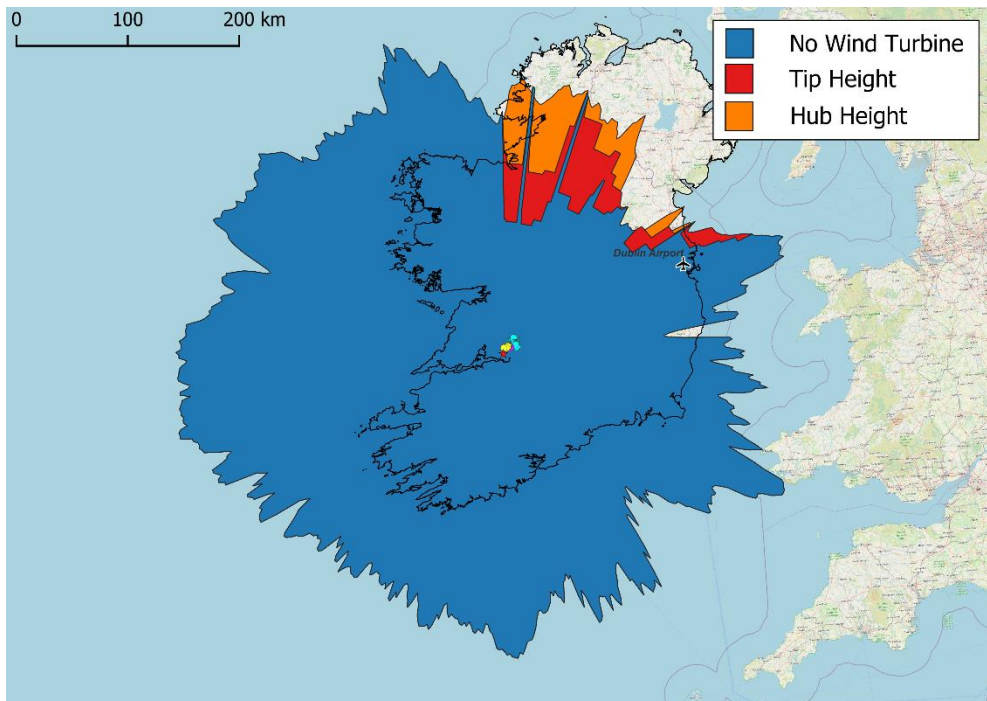


Figure 4.20 Line-of-Sight coverage diagram for a target at 10000 ft AMSL as seen from the MSSR. All consented wind turbines, and the newly planned wind turbines at Knockshanvo and Oatfield are taken into account.

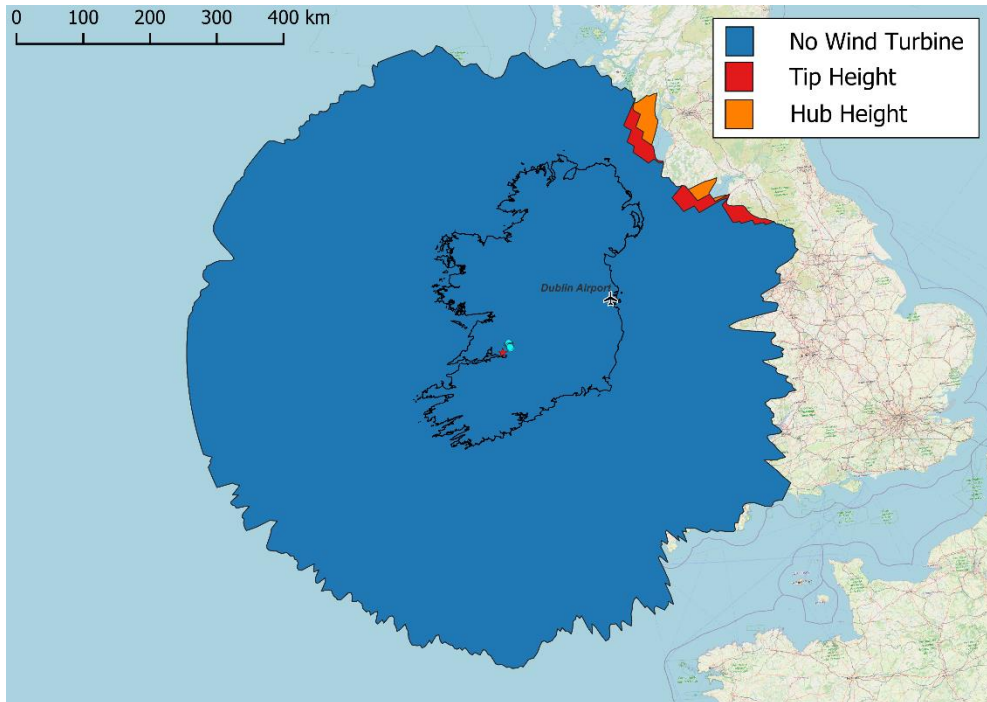


Figure 4.21 Line-of-Sight coverage diagram for a target at 35000 ft AMSL as seen from the MSSR. Only the consented wind turbines are taken into account.

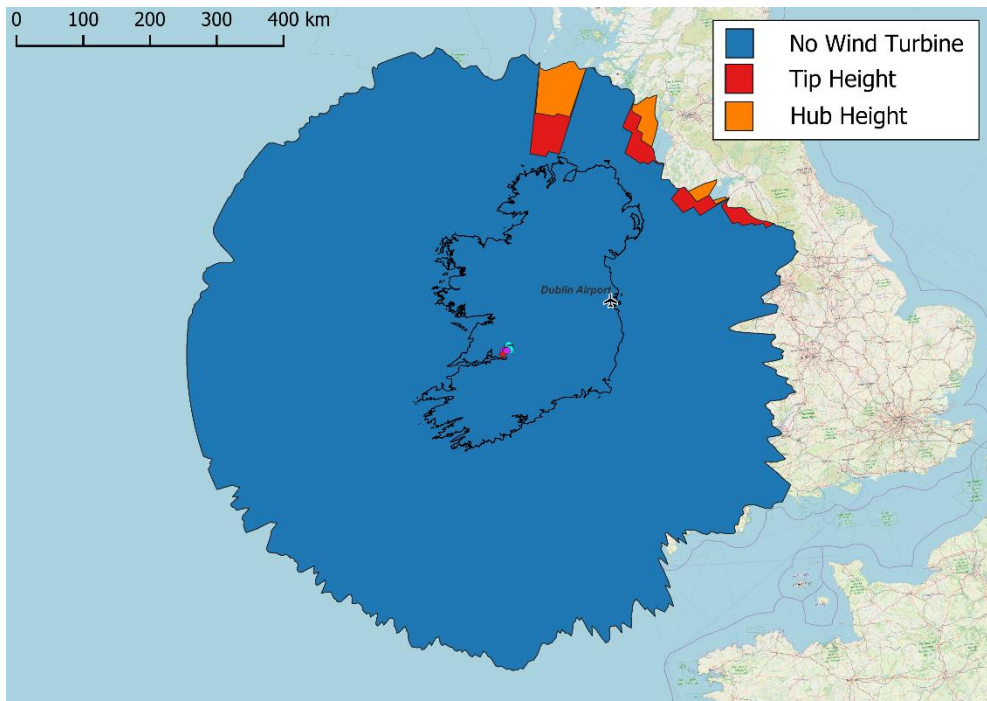


Figure 4.22 Line-of-Sight coverage diagram for a target at 35000 ft AMSL as seen from the MSSR. All consented wind turbines, and the newly planned wind turbines at Knockshanvo are taken into account.

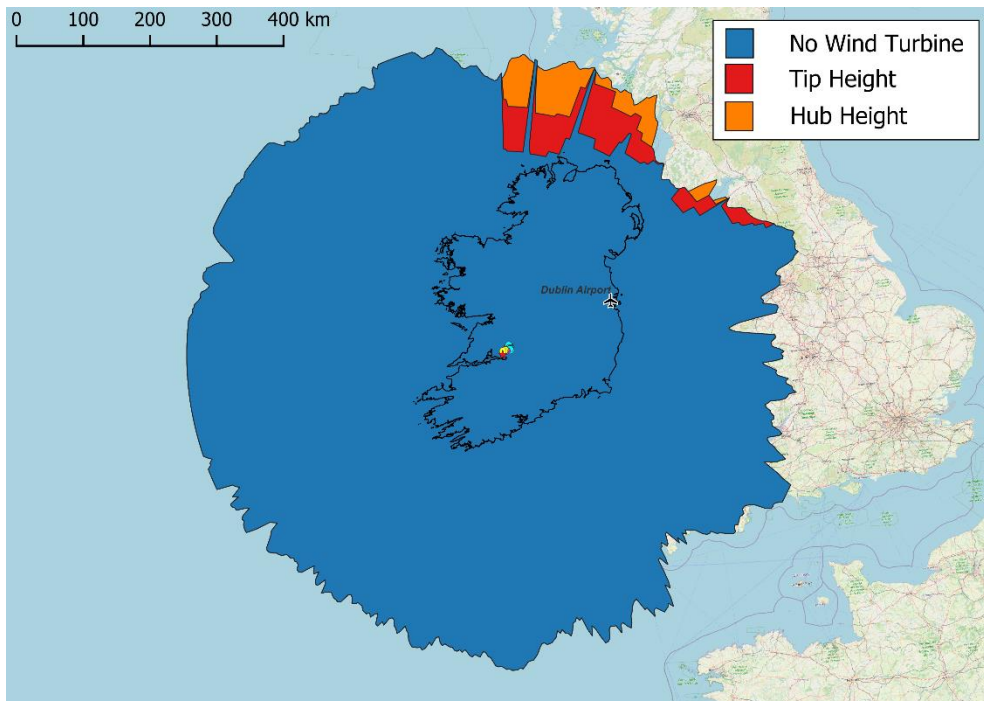


Figure 4.23 Line-of-Sight coverage diagram for a target at 35000 ft AMSL as seen from the MSSR. All consented wind turbines, and the newly planned wind turbines at Knockshanvo and Oatfield are taken into account.

In the figures it can be observed that the situation with the newly planned wind turbines at Knockshanvo result in a zone of additional performance loss at an azimuth sector between approximately  $6^{\circ}$  and  $17^{\circ}$  as seen from the radar. When considering the situation with the newly planned wind turbines at both Knockshanvo and Oatfield, the zone of additional coverage loss is present at an azimuth sector between approximately  $-3^{\circ}$  and  $30^{\circ}$ .

## 4.4 Results of the OBE calculations

As stated in Section 2.1, the presence of an obstacle (like a mountain, building or wind turbine) between the MSSR antenna and the target can cause an error in the estimation of the bearing to the target. In this section, the extent of this bearing error is calculated using a model developed by TNO, in which the method described in Section 2.1 has been implemented.

In this section, the OBE calculations are presented for the MSSR. For the orange and red areas, shown in the figures in the previous section, OBE calculations were carried out. The OBE in the case of the planned wind turbines is determined. The OBE for each area is presented in two different figures for the planned wind turbines, resulting in a total of four figures. Note that the OBE calculations are valid for all flight levels shown in the Line-of-Sight coverage diagrams in the previous section. We only need to do one calculation of the maximum azimuth errors per percentile for all red areas and one for all orange areas.

The results are plotted with a 100<sup>th</sup>-, a 90<sup>th</sup>-, and a 50<sup>th</sup>-percentile plot, in grey, yellow, and dark orange respectively. This is done to give a general overview of the distribution of the off-boresight error for a given azimuth angle. It also shows the same graphs, divided up into azimuth bins, with their values made absolute to create certain azimuth sectors, in which the maximum error can be analysed.

### 4.4.1 MSSR – Orange Area

In Figure 4.24, the OBE for the MSSR as a function of azimuth for the orange area in the previous results for the consented wind turbines is presented, similar to as in Section 2.1 (i.e., the area where the errors originate from the mast and the nacelle). As can be seen, the maximum absolute error is around 0.37° and the azimuth sector influenced by the consented wind turbines ranges from approximately 26° to 65° as seen from the MSSR. For the situation for the consented and newly planned wind turbines at Knockshanvo, this graph is shown in Figure 4.25. As can be seen, the maximum absolute error increases to 0.53° and the azimuth sector due to the newly planned wind turbines ranges from approximately 6° to 17° as seen from the MSSR. The OBE errors for the situation for the consented and newly planned wind turbines at both Oatfield and Knockshanvo are shown in Figure 4.26. It can be seen that due to these newly planned wind turbines located at Oatfield, the OBE increases significantly in the azimuth sector between -3° and 30°.

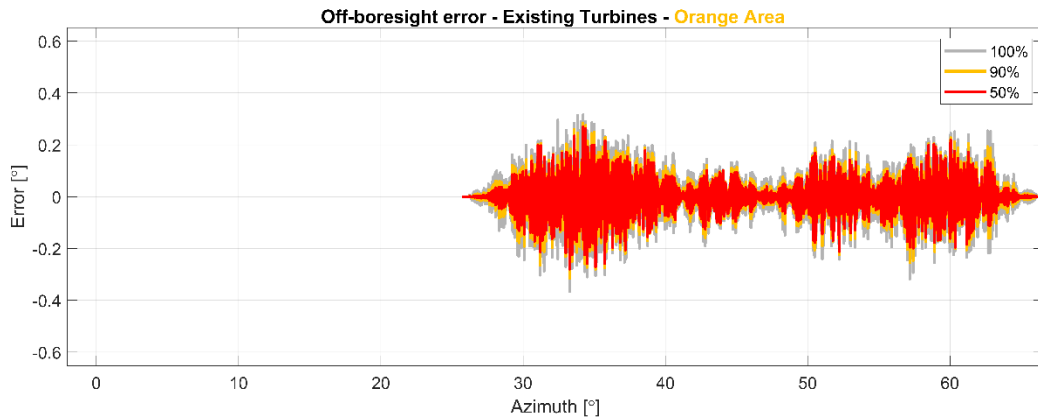


Figure 4.24 The off-boresight error for the consented wind turbines as a function of azimuth for the MSSR in the orange areas of the figures shown in Section 4.3 (i.e., the area where the errors originate from the mast and nacelle).

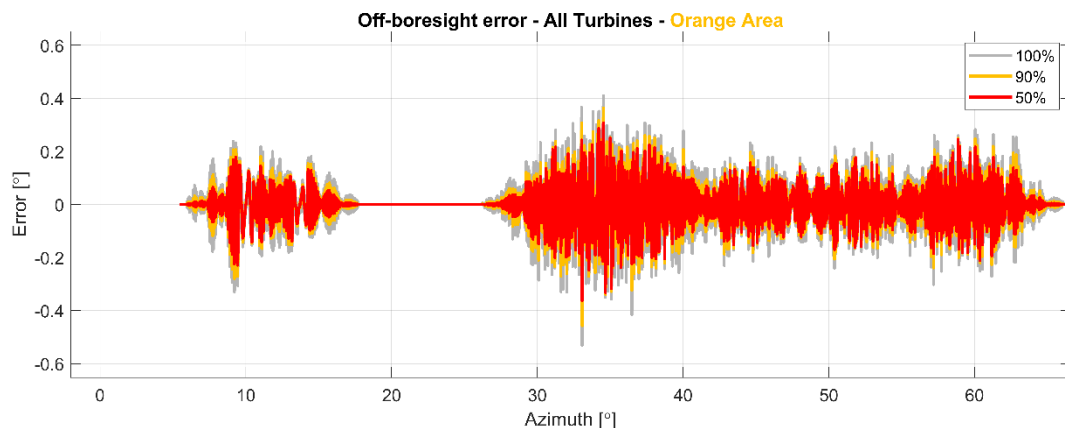


Figure 4.25 The off-boresight error for the consented and newly planned wind turbines at Knockshanvo as a function of azimuth for the MSSR in the orange areas of the figures shown in Section 4.3 (i.e., the area where the errors originate from the mast and nacelle).

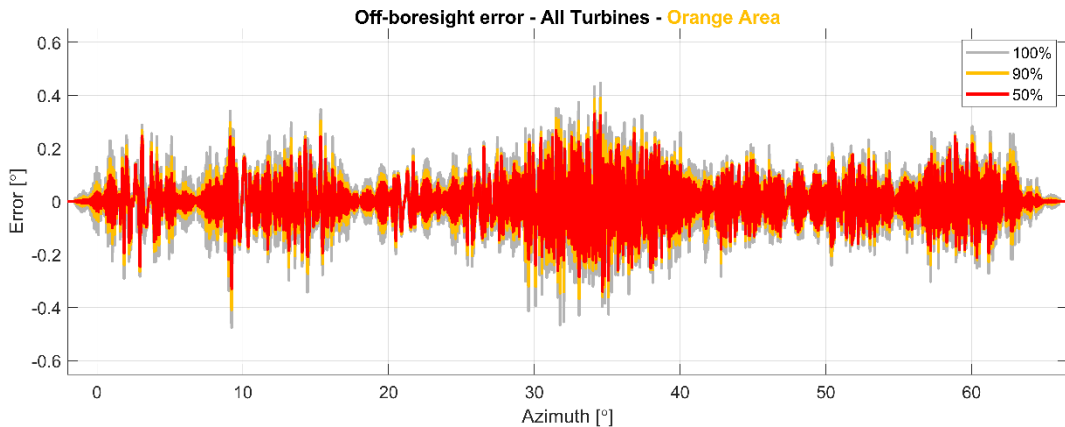


Figure 4.26 The off-boresight error for the consented and both newly planned wind turbines at both Knockshanvo and Oatfield as a function of azimuth for the MSSR in the orange areas of the figures shown in Section 4.3 (i.e., the area where the errors originate from the mast and nacelle).

As can be seen, the OBE fluctuates quite rapidly with azimuth angle. It therefore makes sense to look at the envelope of the graphs. Also, only the absolute value of the error is interesting. In Figure 4.27 we therefore present the same graphs for the situation with the consented wind turbines in a slightly different manner. In these figures, the absolute OBE is grouped per azimuth sector of 1°. For each azimuth sector the value of the 50<sup>th</sup>, 90<sup>th</sup> and 100<sup>th</sup> percentile are shown in red, orange and grey, respectively. The standard deviation, corresponding to a percentile of 68% assuming a normal distribution of the errors, of the OBE is shown as a black dotted line. This distribution is also computed for the situation with the consented and newly planned wind turbines at Knockshanvo and for the situation with the newly planned wind turbines at both Knockshanvo and Oatfield. These distributions are shown in Figure 4.28 and Figure 4.30 respectively.

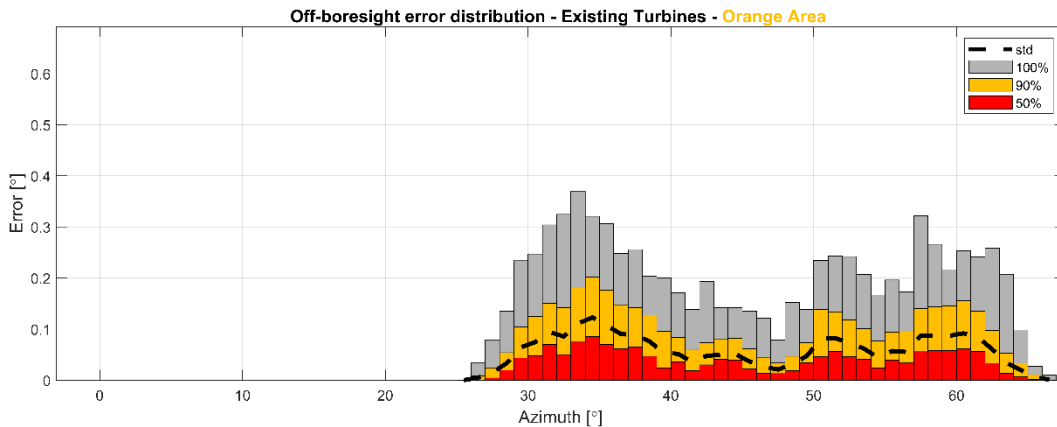


Figure 4.27 The cumulative distribution of the absolute OBE in the orange areas due to the consented wind turbines, per azimuth sector of 1.0°.

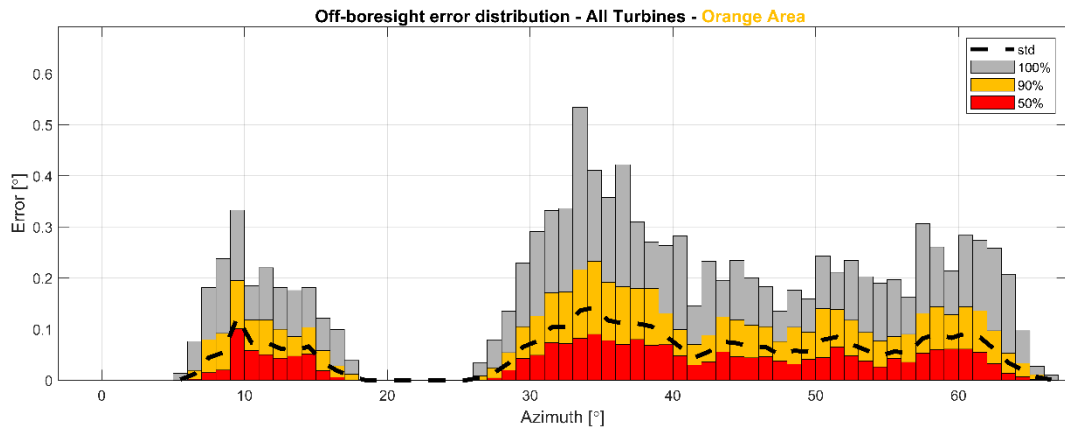


Figure 4.28 The cumulative distribution of the absolute OBE in the orange areas due to the consented and newly planned wind turbines at Knockshanvo, per azimuth sector of 1.0°.

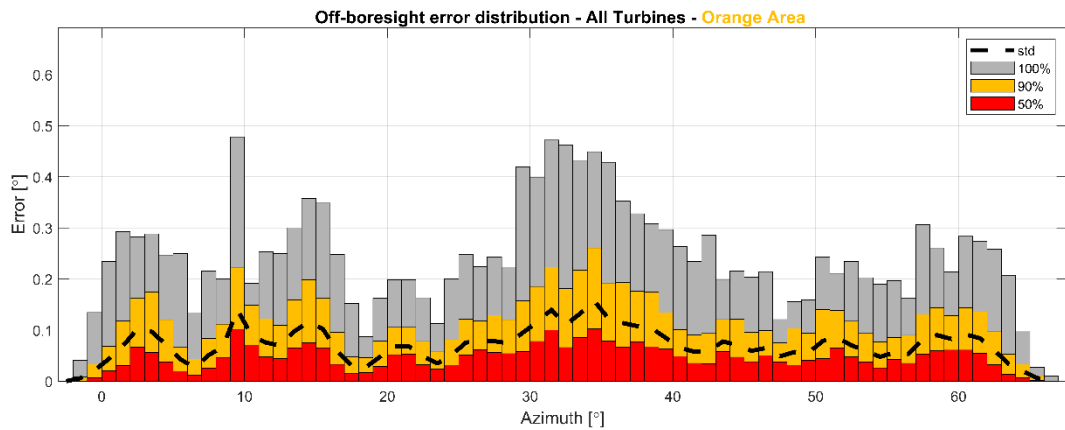


Figure 4.29 The cumulative distribution of the absolute OBE in the orange areas due to the consented and newly planned wind turbines at both Knockshanvo and Oatfield, per azimuth sector of 1.0°.

In the first two situations, the maximum OBE in the orange area occurs at an azimuth of approximately 33° and increases from 0.37° increases to 0.53° in the scenario with only Knockshanvo added and up to 0.48° in the scenario with both Knockshanvo and Oatfield added. It seems odd that the maximum OBE decreases slightly after adding the wind turbines of the Oatfield wind firm. However, this is due to the fact that the presence of each wind turbine can result in a positive error or negative error. Due to the locations of the wind turbines and the geometry with respect to the radar, the errors can be constructively or destructively combined. Moreover, as the 90th percentile indicates, in 90% of the cases, the maximum OBE is less than 0.20° in the initial situation, and increases up to 0.23° when the newly planned wind turbines at Knockshanvo are present, and will increase to 0.26° in the situation with the newly planned wind turbines at both Knockshanvo and Oatfield. In 50% of the cases the maximum OBE is less than 0.10°, in all three situations (i.e., without the newly planned wind turbines, with only the newly planned wind turbines at Knockshanvo, and with the newly planned wind turbines at both Knockshanvo and Oatfield).

## 4.4.2 MSSR – Red Area

In Figure 4.30, the OBE for the MSSR as a function of azimuth in the red area in the previous results for the consented wind turbines is presented (i.e., the area where the errors originate from the blade standing in the upright direction). In Figure 4.33 the absolute OBE is grouped per azimuth sector of 1° and the OBE distribution is shown. For the situation for both the

consented and newly planned wind turbines at Knockshanvo the graphs are shown in Figure 4.31 and Figure 4.35. For the situation for both the consented and newly planned wind turbines at both Knockshanvo and Oatfield the graphs are shown in Figure 4.32 and Figure 4.35.

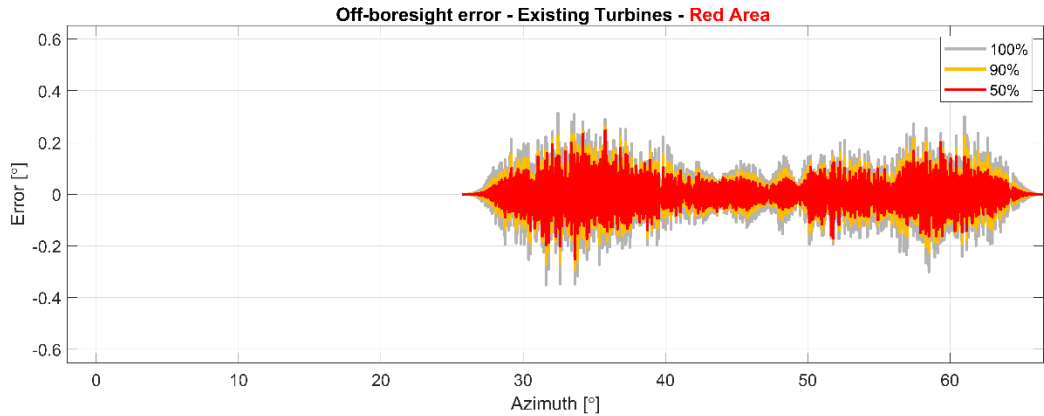


Figure 4.30 The off-boresight error for the consented wind turbines as a function of azimuth for the MSSR in the red areas of the figures shown in Section 4.3 (i.e., the area where the errors originate from the blades).

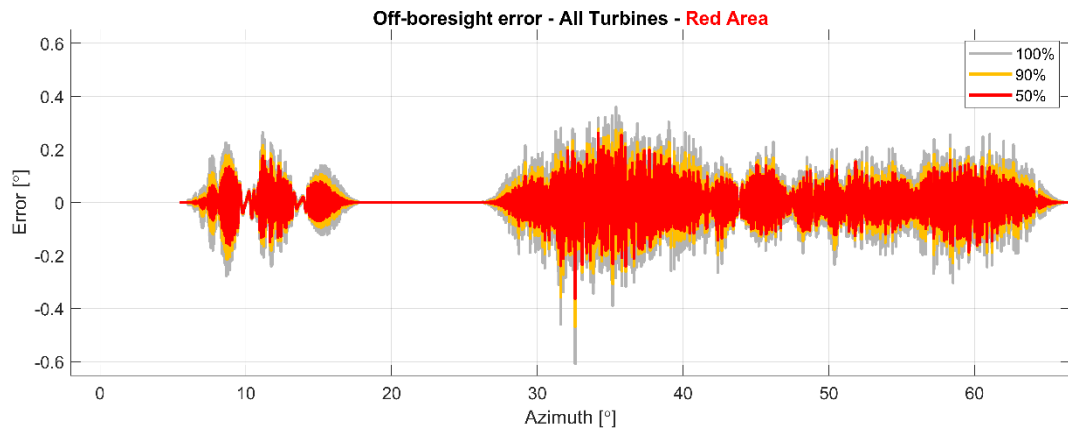


Figure 4.31 The off-boresight error for the consented and newly planned wind turbines at Knockshanvo as a function of azimuth for the MSSR in the red areas of the figures shown in Section 4.3 (i.e., the area where the errors originate from the blades).

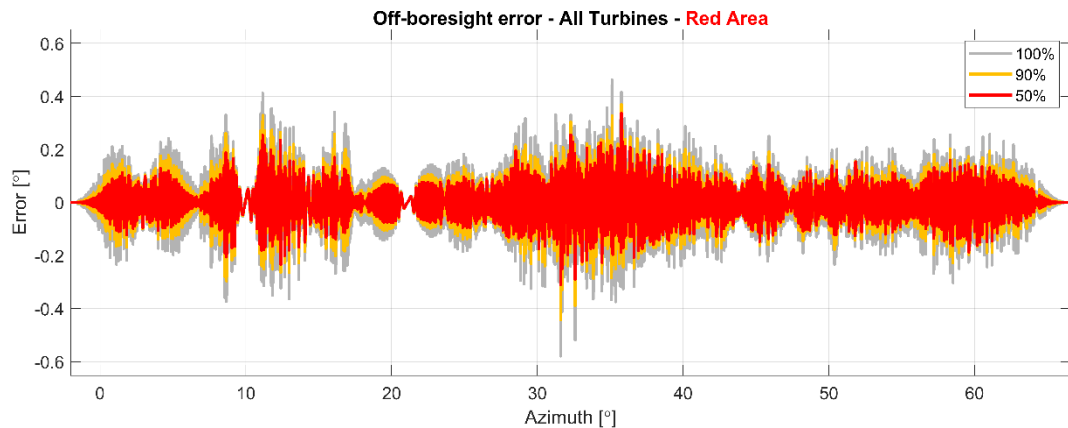


Figure 4.32 The off-boresight error for the consented and newly planned wind turbines at both Knockshanvo and Oatfield as a function of azimuth for the MSSR in the red areas of the figures shown in Section 4.3 (i.e., the area where the errors originate from the blades).

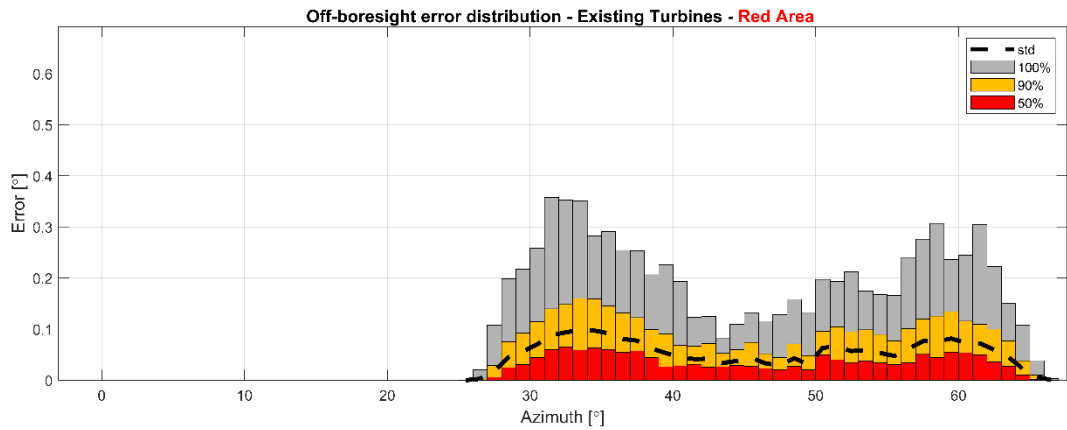


Figure 4.33 The cumulative distribution of the absolute OBE in the red areas due to the consented wind turbines, per azimuth sector of 1.0°.

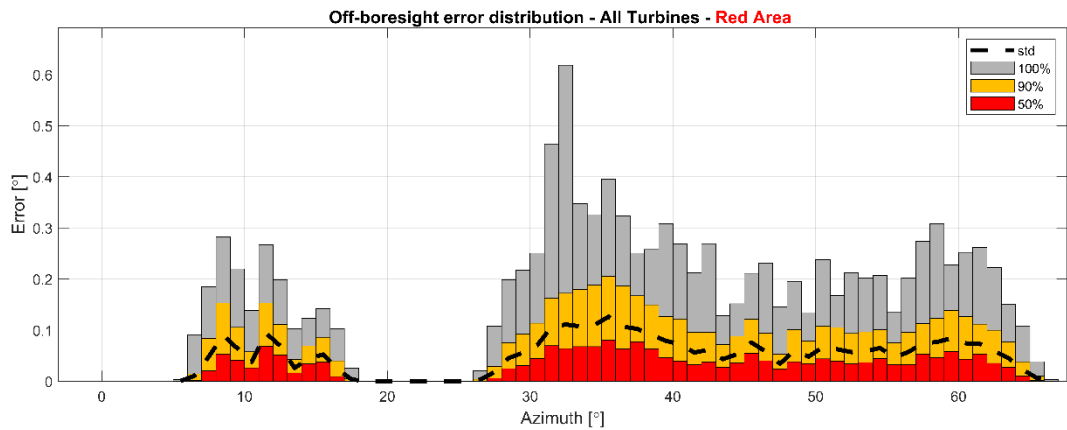


Figure 4.34 The cumulative distribution of the absolute OBE in the red areas due to the consented and newly planned wind turbines at Knockshanvo, per azimuth sector of 1.0°.

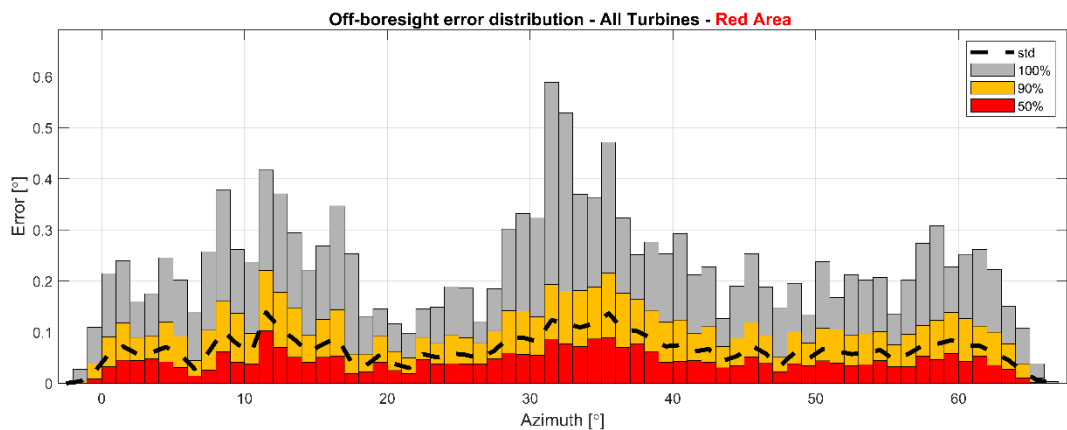


Figure 4.35 The cumulative distribution of the absolute OBE in the red areas due to the consented and newly planned wind turbines at both Oatfield and Knockshanvo, per azimuth sector of 1.0°.

As can be seen in the OBE distribution graphs, the maximum absolute error in the red areas is 0.36° in the initial situation, and increases to 0.62° in the scenario with only Knockshanvo added and up to 0.59° in the scenario with both Knockshanvo and Oatfield added. Similar as for the orange area, as the 90th percentile indicates, in 90% of the cases the maximum OBE increases from 0.16° to 0.21° when the newly planned wind turbines at Knockshanvo are

added and increases up to 0.22° when the wind turbines at Oatfield are added as well. In 50% of the cases the maximum OBE is less than 0.10° for all three situations.

### 4.4.3 Summary of OBE Results

The results of the previous sections are summarized in Table 4.2 for all three scenarios:

1. With only the consented wind turbines considered;
2. With only the newly planned turbine at Knockshanvo added;
3. With the newly planned wind turbines at both Knockshanvo and Oatfield added.

This table shows the maximum 100<sup>th</sup>, 90<sup>th</sup> and 50<sup>th</sup> percentile errors, which are in degrees and describe the error off of true boresight azimuth of a target. The table also shows a standard deviation over the entire azimuth range. Besides, the “Orange Area” describes the situation where only the mast of the turbines is considered, and the “Red Area” describes the situation where both the mast and the rotor are considered.

Table 4.2 OBE statistics of the MSSR in the azimuth with the largest OBE error [°].

Scenario	100%	90%	50%	σ
Before new wind turbines, Orange	0.37	0.20	0.09	0.123
Before new wind turbines, Red	0.36	0.16	0.06	0.099
With new wind turbines at Knockshanvo, Orange	0.53	0.23	0.10	0.143
With new wind turbines at Knockshanvo, Red	0.62	0.21	0.08	0.126
With new wind turbines at Knockshanvo & Oatfield, Orange	0.48	0.26	0.10	0.157
With new wind turbines at Knockshanvo & Oatfield, Red	0.59	0.22	0.10	0.138

As can be observed for the 100<sup>th</sup> percentile and the 90<sup>th</sup> percentile the maximum errors are slightly higher after adding the newly planned wind turbines, and for the 50<sup>th</sup> percentile the maximum expected errors are more or less the same for all three scenarios.

### 4.4.4 Interpretation of the results

As discussed, there exist many different geometries between the target, obstacle (wind turbine) and MSSR antenna. This means that the OBE can be different for two targets at the same azimuth at different moments. For each azimuth sector, the standard deviation is shown as well. For a normal distribution, the standard deviation corresponds to the 68<sup>th</sup> percentile. Here, the error data is not normally distributed. The standard deviation lies between the 50<sup>th</sup> and 90<sup>th</sup> percentile, nonetheless.

Comparing the affected azimuth sectors we see that the OBE extends up to approximately 4.5° to the left and to the right of the wind farm. Outside this 4.5° the OBE will not completely disappear, but it will be much smaller than the overall accuracy of the MSSR of 0.05° RMS. Outside the 4.5° the bearing error will therefore be dominated by other error sources than the wind farm. Note that in Section 4.3 a margin of 5° was assumed. Looking at the results of the OBE, this is indeed a reasonable assumption.

To put the errors in perspective, we can express the OBE in an error in cross-range at a certain distance. By cross-range, we mean the direction perpendicular to the viewing direction of the MSSR.

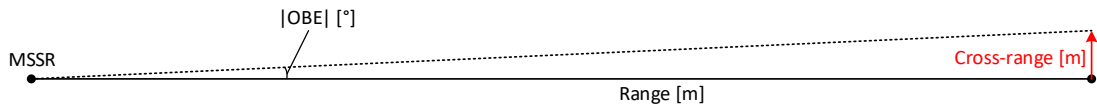


Figure 4.36 Projection of an OBE to a cross-range at a certain range (distance from the radar).

We have done this for the three values mentioned above, *i.e.*, 50, 90, and 100% percentile and for distances from the MSSR of 50, 100, 200, 222, 279 and 474 km. The values are shown below in Table 4.3.

Table 4.3 Example of bearing errors converted into cross-range error in meters for various distances from the MSSR.

OBE	Percentile	Cross-range error					
		Range to target					
[°]	[%]	50 km	100 km	200 km	222 km	278 km	474 km
		27 NM	54 NM	108 NM	120 NM	150 NM	256 NM
0.10	$\sigma$	87 m	175 m	349 m	387 m	485 m	827 m
0.06	50	52 m	105 m	209 m	232 m	291 m	496 m
0.16	90	140 m	279 m	559 m	620 m	776 m	1324 m
0.42	100	367 m	733 m	1466 m	1627 m	2038 m	3475 m

### 4.4.5 Plot error versus track error

Finally, we discuss the influence of the OBE presented in this chapter on the information presented to the operator.

The errors calculated here represent the bearing error on a single reply of the transponder. A worst-case assumption is that the measurement error of a single reply is also the measurement error of the plot, *i.e.* the reported MSSR measurement. In case a plot is derived from multiple replies per dwell, which is generally the case, the measurement error of the plot will be less than the measurement error of a single reply. A tracker processes plots messages and presents track updates of targets on a computer screen to the operator. In general, the error in a plot is also not the same as the error in a track update. Especially when a target does not manoeuvre, positional errors in plots will be ‘smoothed’ by the track algorithm.

## 4.5 Mitigation by other MSSR

The DEA of the MSSR shows that wind turbines within the surveillance area introduce some degradation, expressed as an increased OBE for targets across the instrumented range and at various altitudes. These performance losses indicate that the wind turbines could potentially interfere with the precision of the MSSR in specific areas. To assess potential mitigation, the coverage of a second en-route Mode-S MSSR in the region, the combined PSR and MSSR Tooman, was estimated under the assumption of an undisturbed environment (*i.e.*, assuming that there are no wind turbines in Line-of-Sight of the MSSR).

The radar parameters that are relevant for this analysis are presented in Table 4.4. Note that the coordinates provided by Ai Bridges [3] are slightly different compared to the location on satellite images as can be seen in Figure 4.37, however, this will not affect the results.



Figure 4.37 The combined PSR and en-route MSSR at Tooman Hill housed in a radome. Note that the provided coordinates are slightly off (Image from Google Earth).

Table 4.4 Relevant radar parameters of the combined PSR & Mode-S MSSR Tooman [3].

Parameter	Value
Antenna position	Stand-alone
X (UTM29N)	519760 E
Y (UTM29N)	5841280 N
Latitude (WGS84)	53.555556° N
Longitude (WGS84)	6.250833° W
Height (EGM96)	31 m AGL
	156 m AMSL
Number of elements	35 m
Antenna length	8.5 m
Frequency	1090 MHz
Maximum Instrumented Range	256 NM

The Line-of-Sight coverage diagrams are shown for targets at altitudes of 5000, 7000, 10000 and 35000 ft in Figure 4.38, Figure 4.39, Figure 4.40 and Figure 4.41, respectively. Note that for the calculations of these diagrams only the terrain profile of Ireland and Northern Ireland has been included and not of Great Britain. Therefore the coverage towards the east could be too optimistic. These figures show that the second MSSR provides overlapping coverage with the first MSSR system in the sectors affected by the consented and newly planned wind turbines. Consequently, the second MSSR can serve as an effective redundant system,

ensuring continued surveillance performance and operational robustness in areas where the MSSR at Woodcock Hill experiences reduced performance.

Note that there are potentially even more existing MSSRs that provide coverage in the affected areas of Woodcock Hill, such as the combined PSR and MSSR at Dublin International Airport. This is currently out of the scope of this study.

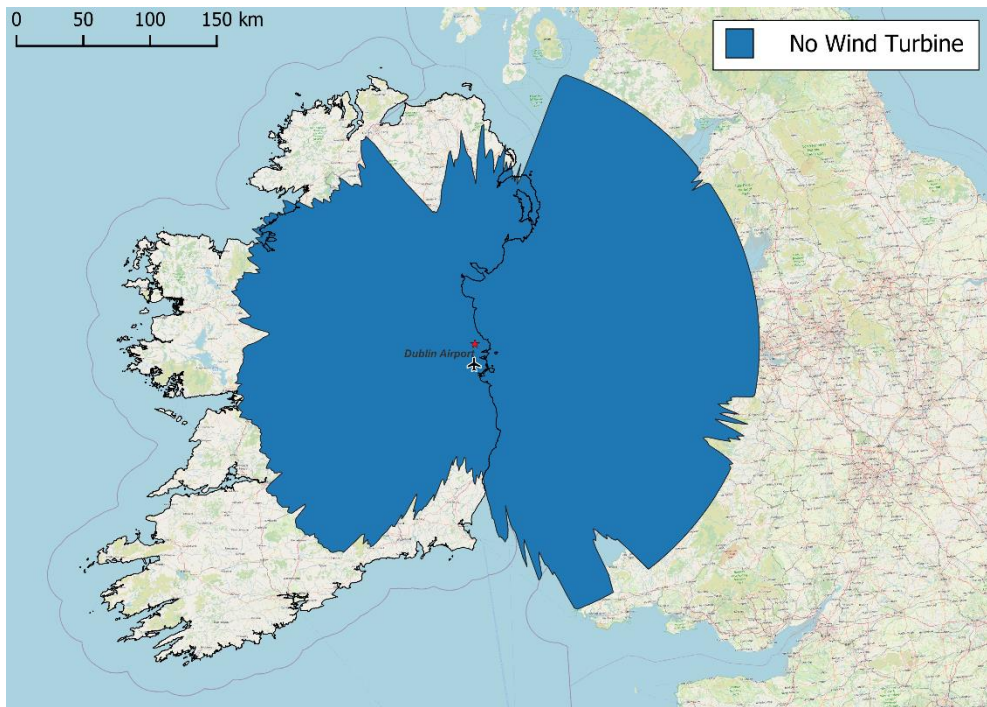


Figure 4.38 Line-of-Sight coverage diagram for a target at 5000 ft AMSL as seen from a secondary MSSR. No wind turbines are taken into account.

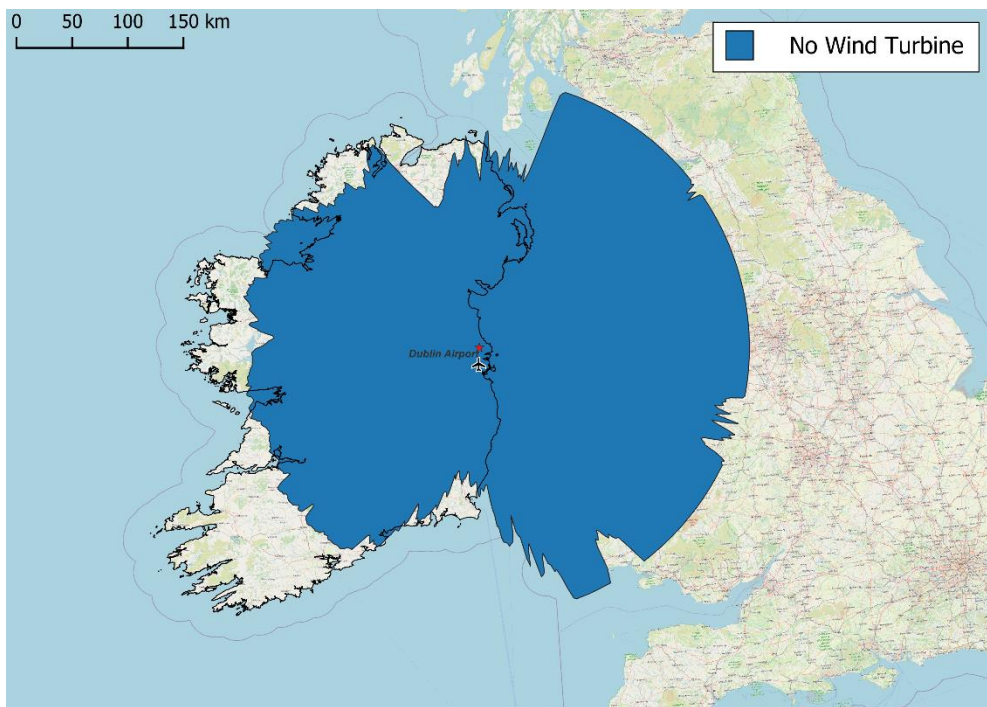


Figure 4.39 Line-of-Sight coverage diagram for a target at 7000 ft AMSL as seen from a secondary MSSR. No wind turbines are taken into account.

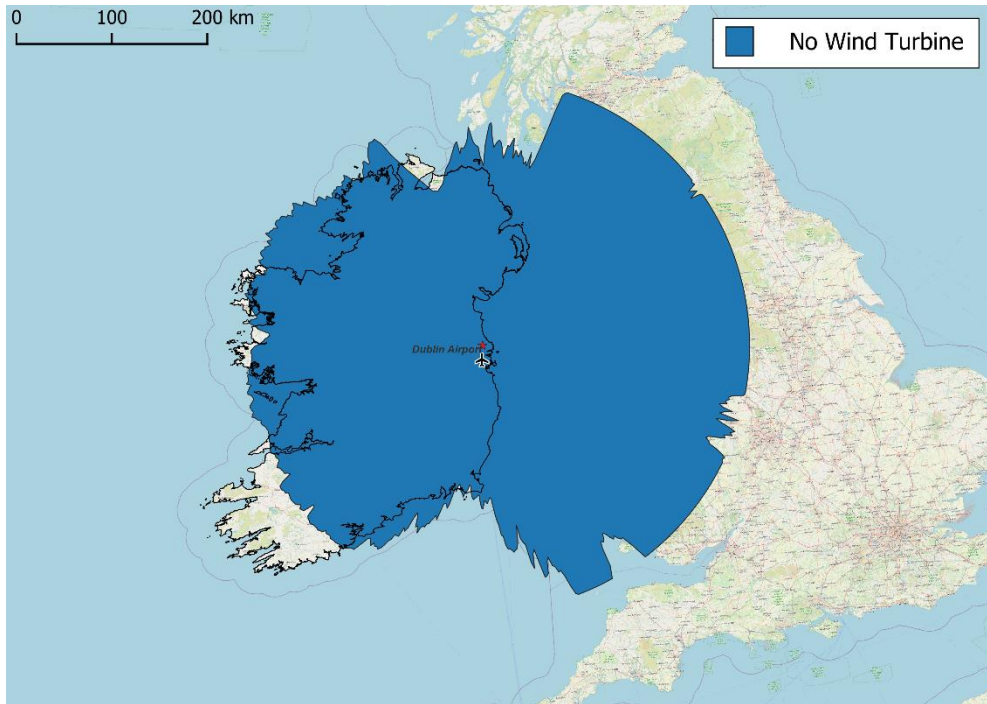


Figure 4.40 Line-of-Sight coverage diagram for a target at 10000 ft AMSL as seen from a secondary MSSR. No wind turbines are taken into account.

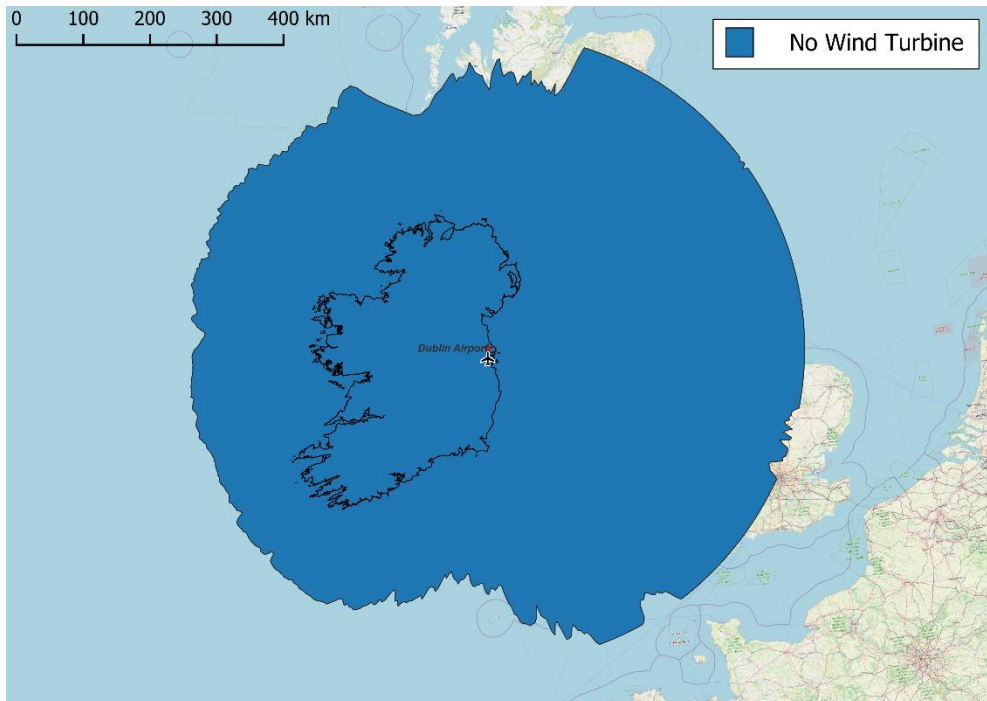


Figure 4.41 Line-of-Sight coverage diagram for a target at 35000 ft AMSL as seen from a secondary MSSR. No wind turbines are taken into account.

## 5 Conclusions

The consented planned wind turbines that have been included in the simulations, have an effect on the MSSR in an azimuth sector of  $39^\circ$ , from  $26^\circ$  to  $65^\circ$ . When the newly planned wind turbines at Knockshanvo are added, an additional region with an azimuth of  $11^\circ$ , from  $6^\circ$  to  $17^\circ$ , that has an effect on the MSSR is present. Subsequently, the additional wind turbines at Oatfield will lead to a further increase of this azimuth sector between  $-3^\circ$  and  $30^\circ$ .

The secondary radar has Line-of-Sight to all wind turbines (see Sections 4.1 and 4.2). The regions where the turbines have an effect on the radar are dependent on the target height and are displayed in Section 4.3. From this, it can be observed that all three situations, with and without the newly planned wind turbines (at only Knockshanvo, and at both Knockshanvo and Oatfield), there could be an effect on the MSSR performance due to the newly planned wind turbines when the target is at a certain area.

The maximum absolute OBE that could occur due to the newly planned turbines at Knockshanvo differ based on the target height. At lower target height, the so-called orange area, where the boresight measurement is interfered by the mast and nacelle, the maximum absolute off-boresight error is found to be  $0.53^\circ$ . At higher target heights, the so-called red area, where the boresight measurement is interfered by only the blade standing in the upright position, the absolute off-boresight error equals  $0.62^\circ$ . The  $1\sigma$  standard deviation value measures  $0.143^\circ$  for the orange area and  $0.126^\circ$  for the red area.

In the situation where the newly planned wind turbines at Oatfield are added as well to the assessment, these errors are slightly different. In this case, the maximum off-boresight error is found to be  $0.48^\circ$  and  $0.59^\circ$  in the so-called orange area and red area, respectively. Also, the  $1\sigma$  standard deviation value is measured at  $0.157^\circ$  for the orange area and  $0.138^\circ$  for the red area.

At last, it has been shown that another existing MSSR (i.e., MSSR Tooman) could provide overlapping coverage in the sectors affected by the consented and newly planned wind turbines, ensuring redundancy and maintaining surveillance performance where the Woodcock Hill MSSR shows reduced performance.

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- [3] Ai Bridges Limited, *Radar details with coordinates and heights primary and secondary radars in Ireland*, 2025 November 12.

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## Appendix H - Service Coverage Maps

Shannon Secondary Radar combined with  
Boolynaglegagh Wind Farm

# Service Coverage Maps

TNO 2026 R10444 – 24 March 2026

## Service Coverage Maps

### Shannon Secondary Radar combined with Boolynaglegagh Wind Farm

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# Abbreviations

<b>Abbreviation</b>	<b>Meaning</b>
ACP	Azimuth Change Pulse
AGL	Above Ground Level
AFB	Air Force Base
AMSL	Above Mean Sea Level
ARB	Auxiliary Reference Burst
ASR	Airfield Surveillance Radar
CAGO	Cell Averaging Greatest Of
CFAR	Constant False Alarm Rate
CTR	Controlled Traffic Region
CUT	Cell Under Test
DEM	Digital Elevation Model
EGM96	Earth Gravitational Model 1996
LVA	Large Vertical Aperture
MRB	Main Reference Burst
MSSR	Monopulse Secondary Surveillance Radar
NASA	National Aeronautics and Space Administration
NGSP	Next Generation Signal Processor
OBE	Off Boresight Error
PSR	Primary Surveillance
RCS	Radar Cross section
RPM	Revolutions Per Minute
SSR	Secondary Surveillance Radar
SRTM	Shuttle Radar Topography Mission
SWG	Slotted Wave Guide
TNO	Netherlands Organisation for Applied Scientific Research
VCC	Vertical Clutter Cancellation
WC	Worst-case
WT	Wind Turbine
WFF	Wind Farm Filter
WGS84	World Geodetic System 1984

# 1 Introduction

The performance of radar systems can be negatively influenced by wind turbines in their vicinity. EUROCONTROL has issued guidelines, on how to assess the potential impact of wind turbines [1].

Ai Bridges has requested to prepare the Service Coverage map of the en-route MSSR at Shannon and identify the areas where the angle measurement of the MSSR may be influenced by the wind turbines of the existing Boolynaglegagh wind farm. The closest wind turbine is located at approximately 15.5 km from the secondary radar at Shannon.

In Section 2 the general information is given and in Section 3 the specific input parameters of the relevant wind turbines and radar for this study are given. In Section 0, we determine the service coverage maps of the MSSR at Shannon without and with the wind turbines at Boolynaglegagh.

## 2 General Information

### 2.1 Effects of wind turbines on MSSR

The presence of wind turbines can influence the performance of MSSRs. In order to correctly interpret the results of the Line-of-Sight analysis, we address the most important issue that can arise whenever a wind farm is near a secondary radar system: bearing errors. Apart from bearing errors a wind turbine also creates a shadow. In contradiction to an optical shadow, a wind turbine in the line-of-sight path will affect visibility, but not in all cases will cause the target to be invisible. This principle is illustrated in Figure 2.1. Radio waves diffract around an obstacle, limiting the shadow zone directly behind an obstacle. Due to the fact that energy is reflected back from the wind turbine the presence of a wind turbine will cause a loss in maximum detection range.

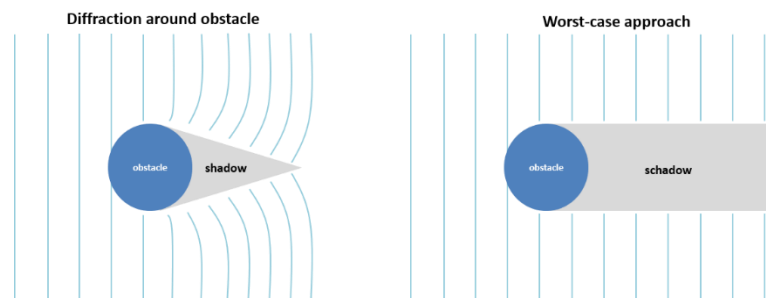


Figure 2.1 Graphical illustration of diffraction effects.

Note that the amount of diffraction is frequency dependent. At lower frequencies there is more diffraction, resulting in a lower loss in detection range. At higher frequencies, there is less diffraction, or the radio wave behave more light-like. This results in a higher loss of detection range.

SSRs differ from PSRs in several ways. PSRs do not depend on cooperation of aircraft, they merely measure range, bearing and sometimes also elevation angle and radial velocity. SSRs demand that aircraft cooperate, *i.e.*, the aircraft actively participates in its detection. The SSR sends out an interrogation signal at 1030 MHz. The target, carrying a radar transponder, subsequently replies by transmitting a response signal at 1090 MHz. This response contains additional information regarding the target, *e.g.*, barometric altitude (mode C) and an identity code (mode A). In the case of monopulse SSR (MSSR), the system is capable of making a precise bearing estimate of the target from a single reply signal (hence, monopulse). The bearing estimate is generally accurate within a fraction of a degree ( $\sim 0.05^\circ$ ). The presence however of an obstacle (like a mountain, building or wind turbine) between the MSSR antenna and the target can cause an error in the estimation of the bearing to the target.

In Figure 2.2 an MSSR antenna is shown, typically comprising 35 antenna elements. Below we first give a short description on how the bearing measurement is carried out and how the wind turbine influences this measurement.



Figure 2.2 The secondary radar antenna, comprising of 35 antenna elements, on top of a STAR 2000 antenna.

The bearing to a target is determined using the so-called monopulse technique. By applying different weight factors for each antenna element, two radar beams are created with the same antenna, the so-called *sum beam* and *difference beam*, see Figure 2.3. A reply is received by both beams. By comparing the signal strength in the sum beam to the signal strength in the difference beam an accurate bearing angle can be estimated. Left-right ambiguity is solved by looking at the phase of the signal. For example, when the sum and difference beam record a pulse with the same signal strength, looking at Figure 2.3 we see that the bearing to the target must be, depending on the phase, either  $+1^\circ$  or  $-1^\circ$ .

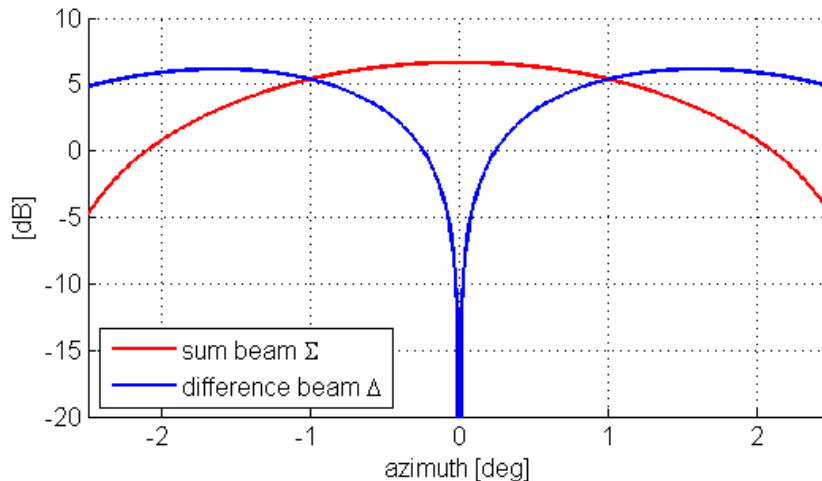


Figure 2.3 The sum beam (red) and difference beam (blue) used within the TNO model. The bearing of the target is estimated by comparing the signal strength of a single reply signal in both beams.

If a wind turbine is positioned between the target and the radar, the received electric field is distorted both in phase and in amplitude. This is illustrated in Figure 2.4. The distorted field effectively changes the weight factor at each antenna element, thus, changing the shape of the sum beam and difference beam. As the two beams are influenced differently by the wind turbine, so is the signal strength measured in both beams. Therefore, when the signal strength is compared to estimate the bearing, an error is introduced.

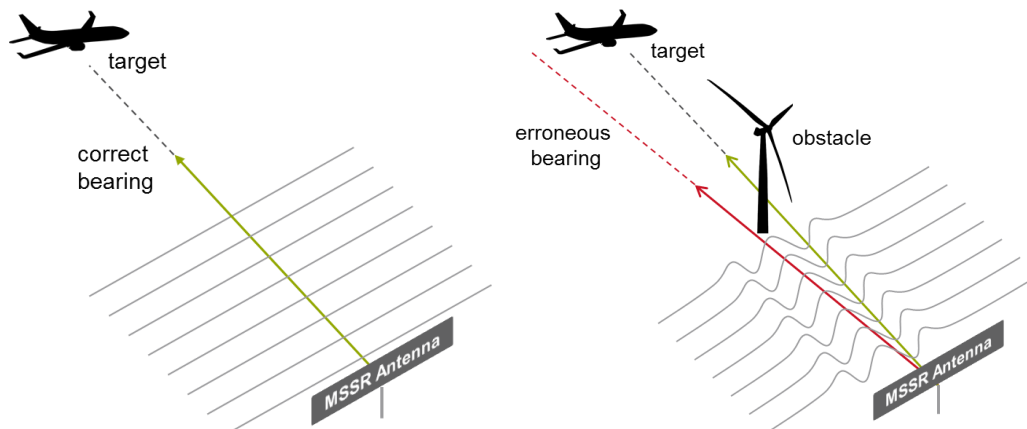


Figure 2.4 A wind turbine, positioned between target and MSSR antenna can disturb the transponder signal, introducing an error in the bearing estimate.

The bearing error as a function of azimuth angle to the target has been calculated. This will give us insight in the width of the zone in which the MSSR is influenced by the wind turbine. To estimate the bearing error, we use an analytical solution for an incident plane wave on a cylinder with fixed radius and infinite length. The method calculates the phase and amplitude of the perturbed wave front on each antenna element. From this the bearing error is determined. The method is described in full in [2]. In this reference the method has been validated using real data of an MSSR partially obstructed by a metal mast of width ~2 meter at a range of approximately 600 meter.

TNO has conducted its own validation of the method as well using real MSSR data. In this validation the MSSR is partly obstructed by an ATC tower with a maximum width of 20 meter at a range of approximately 2 km. In both cases, the calculated bearing error as a function of azimuth matched relatively well with the measured data. Figure 2.5 shows the close match between real recorded MSSR track of an aircraft at a distance around 175 km from the MSSR and the simulated data. Secondary effects at coordinates [4, 178] and [-4, 174] km appear accurately modelled as well (indicated by red arrows).

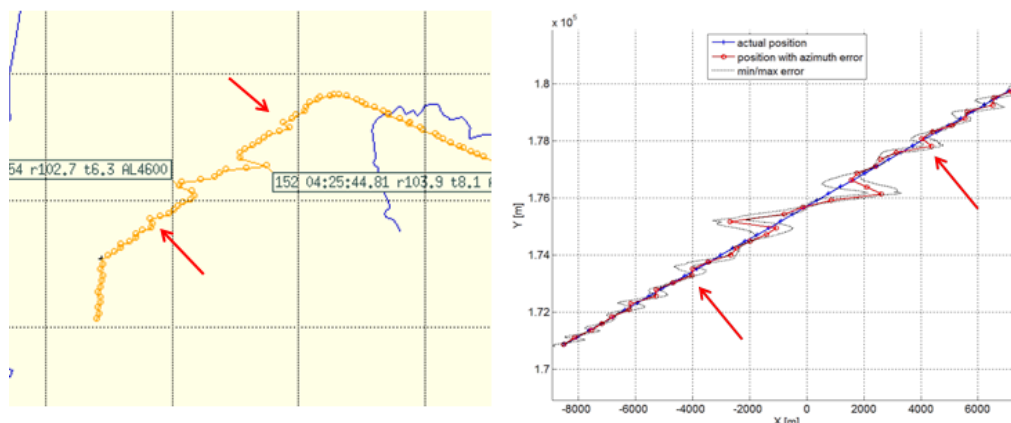


Figure 2.5 Comparison of a MSSR track recoding of a real aircraft and the simulated results. Secondary effects at coordinates [4, 178] and [-4, 174] km appear accurately modelled as well (indicated by red arrows).

As mentioned, the method uses a cylinder of infinite length to model the obstacle. An infinite cylinder can be described by just a single parameter, its width. In our simulations we have

chosen the width of the cylinder to be dependent on whether or not the nacelle or blades can be seen by the radar, see Figure 2.6. In the orange sector, the width of the cylinder is equal to the average of the width and length of the nacelle. In the red sector, the width of the cylinder for all visible wind turbines is set to the width of the blade, see Figure 2.6.

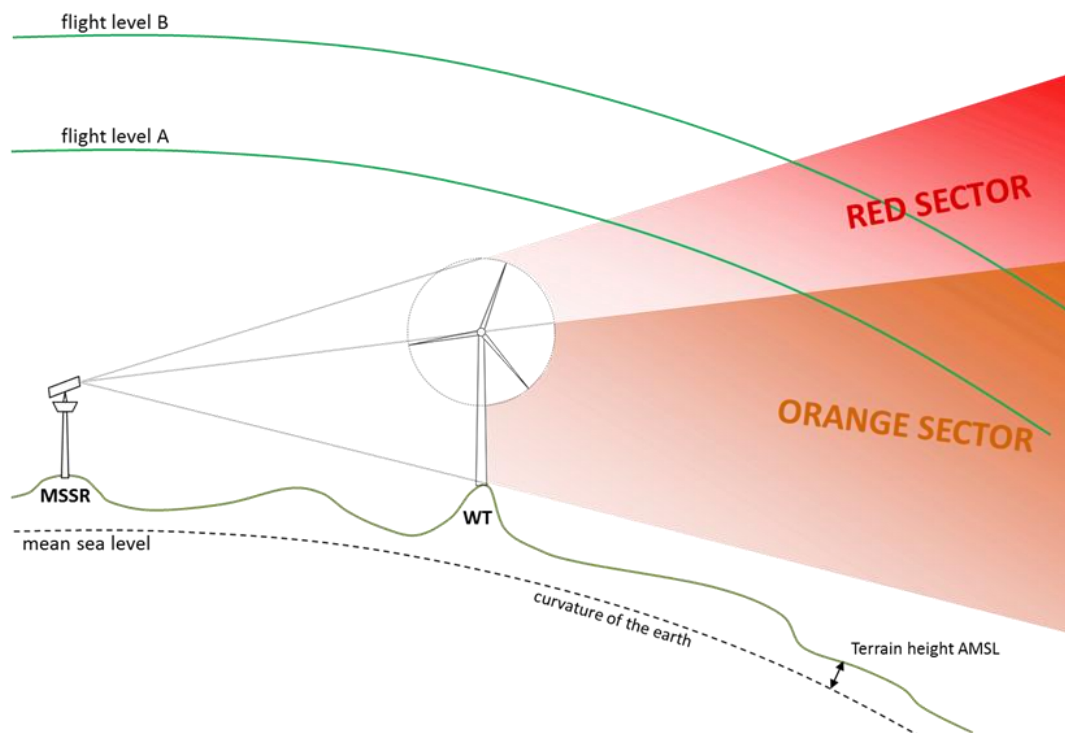


Figure 2.6 The orange and red areas, shown in the LoS coverage diagrams are in fact cuts through a volume behind the wind turbines. The calculated OBE (Off Boresight Error) is thus valid at all flight levels shown in the LoS coverage diagrams.

It is assumed that there is always a wind turbine blade with a vertical orientation. The full tip height of the turbine is used in the analysis. As there is not always a wind blade directed vertically, this is a worst-case assumption.

Furthermore, the applied method describes the incoming signal as a plane wave (as depicted in the left image of Figure 2.4). The approximation of the incoming radiation as a plane wave is valid in case the distance between the target and the obstacle is sufficiently large. To see whether the plane wave approximation is valid, we calculate at which distance the phase difference between the two ends of the wind turbine blade is equal to half a wavelength. The path difference  $\Delta r$  from one end of the blade to the other can be approximated by  $\Delta r = L^2/2R$ , where  $L$  is the length of the blade and  $R$  is the range. Setting  $\Delta r$  equal to half a wavelength,  $\lambda/2$ , and filling in for this example  $L = 60.7$  meter, we find  $R = 13$  km at 1090 MHz. We see that the incoming wave for a target at 13 km behind the obstacle already resembles a plane wave quite closely. For targets at larger distances the resemblance will be even better. For targets closer than 13 km to behind the wind turbine, the estimated bearing error is a first order approximation.

Regarding the geometry of the situation, we consider two parameters: (1) the azimuth angle to the target, relative to the obstacle and (2) the orientation of the radar antenna at the moment that the transponder reply is received. Given a wind turbine at a certain azimuth angle,  $\alpha$ , we let the target move from  $\alpha - 4^\circ$  to  $\alpha + 4^\circ$  in 501 steps. At more than  $4^\circ$  azimuth

from the wind turbine the error reduces rapidly to values much smaller than the accuracy of the MSSR (typically  $0.05^\circ$ ). For each position of the target, the radar antenna is rotated over  $3^\circ$ , from  $-1.5^\circ$  to  $1.5^\circ$ , where  $0^\circ$  corresponds to the antenna looking directly at the target. For each geometry the disturbed electric field is calculated. This is done for each (visible) wind turbine in the wind farm separately. Subsequently, all disturbed fields are summed and the bearing error for the total field is calculated.

A typical example of the Off-Boresight Error (OBE) for a single obstacle (i.e., cylinder width 25 meter) at a range of 3 km is shown in Figure 2.7. The obstacle is located at an azimuth angle of  $218.5^\circ$ . At a given azimuth angle, the error is in 100% of the cases contained within the two grey lines, in 90% of the cases between the two orange lines. The OBE at a given azimuth angle is thus not a single number, but lies in the range defined by the two lines of the same colour. The reason this happens, is that, as mentioned above, the geometry between the rotating antenna, target and obstacle can differ for a target at a given azimuth. The grey line thus gives the upper limit of the bearing error to be expected at a given azimuth angle. This is the case when the radar antenna is in the least favourable orientation when receiving the reply signal.

As can be seen in the figure below the OBE caused by a single obstacle is point symmetrical around the azimuth to the obstacle. Directly behind the obstacle, the error is zero. In this case the sum and difference beams are equally disturbed, resulting in no error of the estimated azimuth angle. Note that in the case of multiple obstacles at different ranges, the symmetry is broken.



Figure 2.7 The off-boresight error for an infinite cylinder with a width of 25 m at a range of 3 km from the radar antenna. The error is point symmetrical around the azimuth angle to the obstacle.

# 3 Specific Input Parameters

## 3.1 Wind turbines

The service coverage maps have been determined for the combined PSR and MSSR at Shannon in combination with the existing Boolynaglegagh windfarm comprising sixteen wind turbines. No other wind turbines are considered. An overview of the situation is provided in Figure 3.1. The yellow dots indicate the wind turbines under investigation. The distance between the secondary radar at Shannon and the closest wind turbine of the windfarm under investigation measures approximately 15.5 km.



Figure 3.1 The locations of the existing Boolynaglegagh windfarm (yellow dots). The secondary radar at Shannon is indicated by the red star. Image taken from OpenStreetMap.

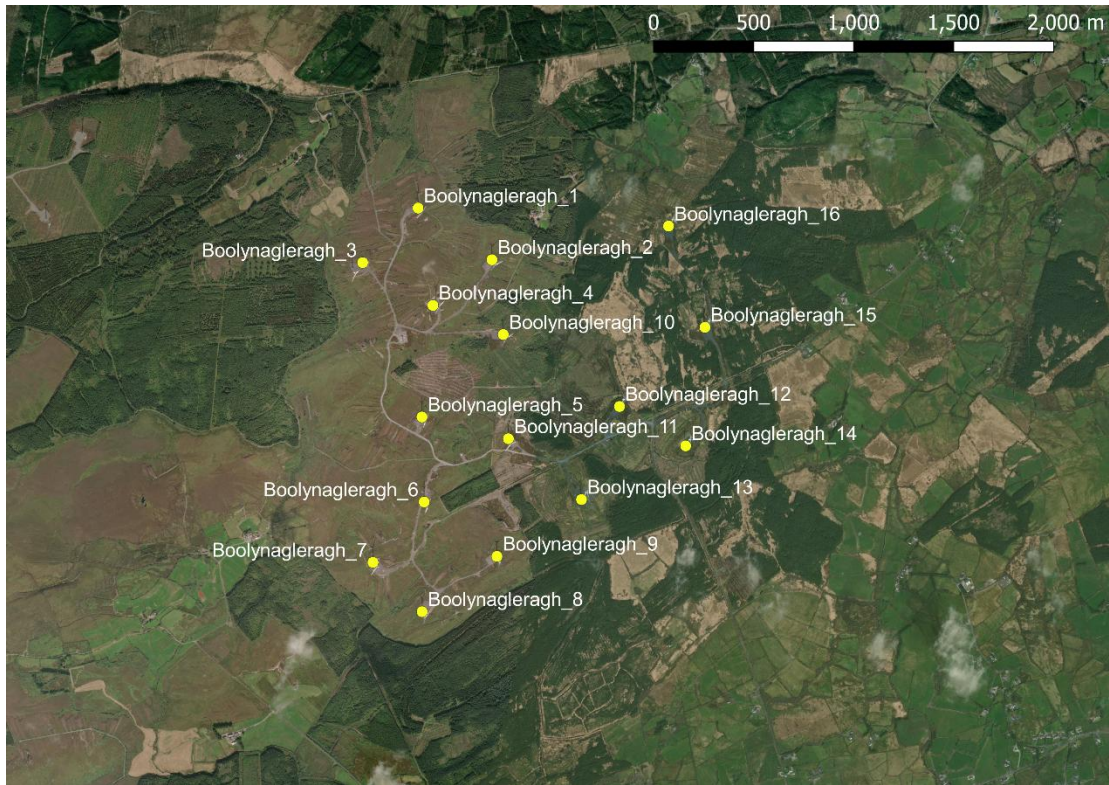


Figure 3.2 The locations of the existing Boolynagleragh windfarm (yellow dots). Image taken from Bing.

The wind turbine type at Boolynagleragh wind farm is the N100 from Nordex. They all have a hub height of 80 m and a rotor diameter of 100 m, resulting in a tip height of 125 m.

In Table 3.1 an overview is presented of the positions, types, hub and tip heights of the existing wind turbines of Boolynagleragh wind farm. This information has been received from Ai Bridges.

Table 3.1 Overview of the positions, type and tip heights of the already consented wind turbines near the newly planned wind turbines. which have been provide by Ai Bridges.

Nr.	Name/Owner	ID	Lat [°]	Lon [°]	Terrain [m]	Type	Hub [m]	Tip [m]
1	Boolynaglegagh	Boo-01	52.78658	-9.15205	206	N100	80	125
2	Boolynaglegagh	Boo-02	52.78497	-9.14592	183	N100	80	125
3	Boolynaglegagh	Boo-03	52.78368	-9.15527	203	N100	80	125
4	Boolynaglegagh	Boo-04	52.78243	-9.14953	191	N100	80	125
5	Boolynaglegagh	Boo-05	52.77742	-9.14867	177	N100	80	125
6	Boolynaglegagh	Boo-06	52.77370	-9.14725	179	N100	80	125
7	Boolynaglegagh	Boo-07	52.77058	-9.15007	165	N100	80	125
8	Boolynaglegagh	Boo-08	52.76885	-9.14577	164	N100	80	125
9	Boolynaglegagh	Boo-09	52.77196	-9.14116	167	N100	80	125
10	Boolynaglegagh	Boo-10	52.78178	-9.14399	178	N100	80	125
11	Boolynaglegagh	Boo-11	52.77724	-9.14207	157	N100	80	125

Nr.	Name/Owner	ID	Lat [°]	Lon [°]	Terrain [m]	Type	Hub [m]	Tip [m]
12	Boolynaglegagh	Boo-12	52.77966	-9.13448	139	N100	80	125
13	Boolynaglegagh	Boo-13	52.77522	-9.13586	158	N100	80	125
14	Boolynaglegagh	Boo-14	52.77852	-9.12909	131	N100	80	125
15	Boolynaglegagh	Boo-15	52.78391	-9.12945	145	N100	80	125
16	Boolynaglegagh	Boo-16	52.78804	-9.13359	149	N100	80	125

For determining the service coverage maps only the hub height and tip height are required.

### 3.2 Secondary Radar at Shannon

The radar is part of a combined STAR 2000 PSR and Mode-A/C MSSR located at Shannon International Airport in the west of Ireland, see Figure 3.3. The main parameters that are relevant for this study are presented in Table 3.2.



Figure 3.3 The combined PSR and Mode-A/C MSSR at Shannon International Airport (Image source: Street View).

Table 3.2 Relevant radar parameters of the combined PSR and Mode-A/C MSSR at Shannon [3].

Parameter	Value
Antenna position	Combined with PSR
X (UTM29N)	504285 E
Y (UTM29N)	5839056 N
Latitude (WGS84)	52.70140° N
Longitude (WGS84)	8.93659° W
Height (EGM96)	21.3 m AGL
	35.6 m AMSL
Maximum Instrumented Range	250 NM

# 4 Service Coverage maps

In this section we identify the areas where the presence of wind turbines could affect the performance of the stand-alone MSSR at Shannon. To do this, we first carry out the so-called Line-of-Sight (LoS) analysis for the MSSR. This analysis will give insight into the visibility of the wind farm as seen from the MSSR's position.

To perform the Line-of-Sight analysis, a Digital Elevation Model (DEM) is required. The terrain altitude data in the DEM is taken from the Shuttle Radar Topography Mission (SRTM) database that has a resolution of approximately 25 meters. In Figure 4.1 an overview of the terrain altitude is shown. As can be observed, the terrain is a bit hilly. The radar location is shown, as well as the locations of the existing wind turbines of Boolynaglegagh wind farm.

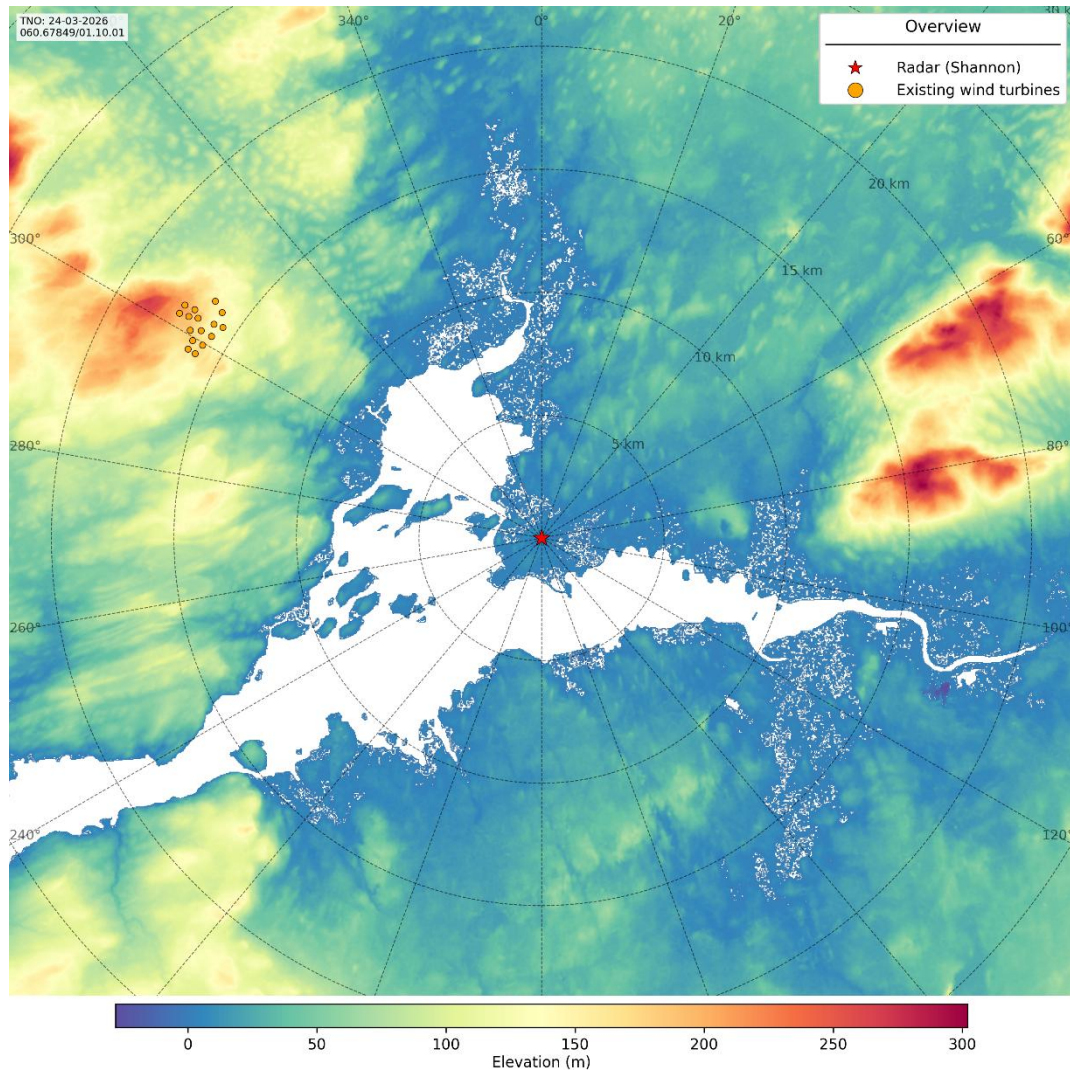


Figure 4.1 Height map around the existing wind turbines of Boolynaglegagh wind farm and the MSSR at Shannon (red star).

## 4.1 Radar horizon

In this section we show the extent of the wind farm in azimuth and elevation for the MSSR. These results reveal whether the wind farm has impact on the radar horizon. A wind turbine influences the radar horizon when the elevation angle to the tip height of the wind turbine is larger than the elevation angle to all other objects at the same azimuth angle, extending all the way up to the instrumented range of the MSSR, which measures 250 NM. Given the elevation angle to the tip height, aircraft at different altitudes are influenced at different ranges as shown in Figure 4.2. Here, the elevation angle to the tip height of the wind turbine is indicated by a grey line. The MSSR replies of aircraft above this line are not influenced by the wind turbine. Aircraft replies below the line may be influenced by the wind turbine.

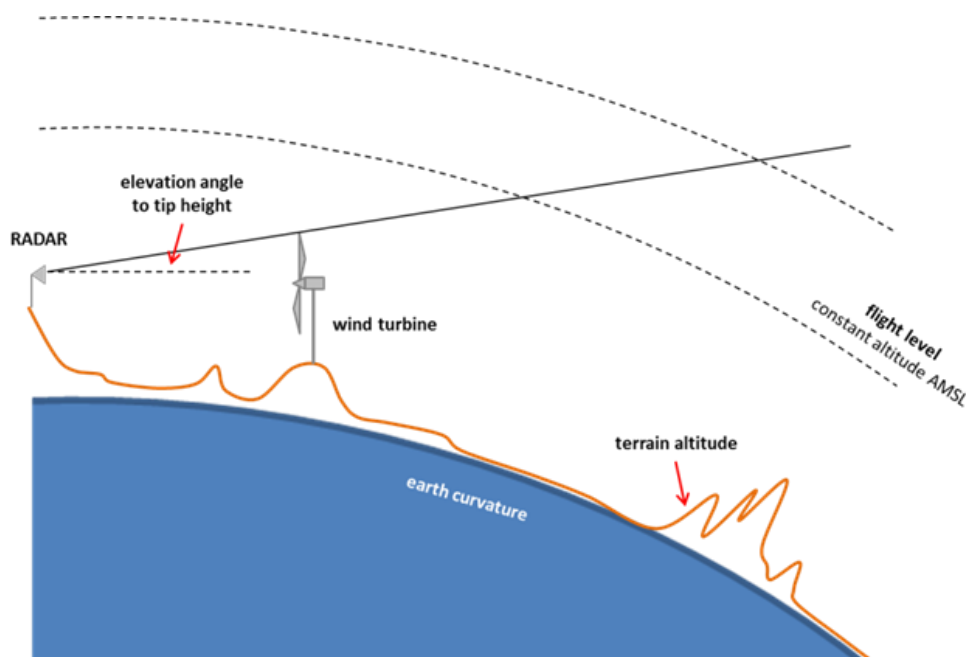


Figure 4.2 Overview of the overall Line-of-Sight geometry at fixed azimuth.

Note that this line-of-sight analysis considers both the curvature of the Earth as well as the shape of the terrain. Electromagnetic waves do not follow straight lines but tend to curve along the surface of the Earth to some extent as the refractivity index of the air varies with altitude. These refraction effects are generally considered by multiplying the radius of the Earth by a so-called  $k$ -factor. A common value for the  $k$ -factor is 1.33, which has been used in all results. By using the  $k$ -factor, we can treat the radio waves as if travelling along straight lines instead of curved lines.

In the next figure we show azimuth-elevation plots of the surrounding terrain (the radar horizon) including the wind farm. An orange (new) or green (existing and authorised) line indicates the wind turbine up to the tip height. The horizontal red lines indicate the blades of the wind turbine at hub height. Note that the scaling of the horizontal and vertical axes in these figures is different. This means that the wind turbines appear high and narrow. The width of the blades in the horizontal direction (azimuth) is in fact the actual width of the wind turbine as seen from the radar.

As can be seen in Figure 4.3 the radar has Line-of-Sight to the existing wind turbines of Boolynaglegagh wind farm. The turbines are located at approximately 297° to 307° in azimuth with respect to the North as seen from the radar’s location.

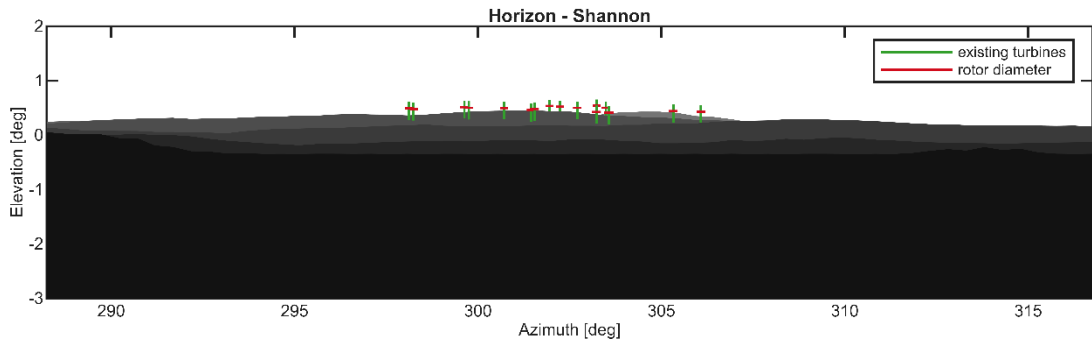


Figure 4.3 Horizon of the existing wind turbines of Boolynaglegagh wind farm as seen from the MSSR.

## 4.2 Line-of-Sight to individual wind turbines

Next, we look at the Line-of-Sight to the individual wind turbines as seen from the MSSR. From these figures we can draw conclusions on aircraft ranges and altitudes at which the wind turbine potentially interferes with MSSR operations.

The red line in each figure represents 0 m AMSL. The black line above the red line shows the terrain altitude along the azimuth line towards the wind turbine. The radar is indicated by a red triangle on the left of each figure. The wind turbine is drawn at its corresponding range in each figure. The first Fresnel zone towards the tip and hub heights of the wind turbine are drawn as dashed red and blue ellipsoids, respectively.

A dashed black line passes through the point on the ground with the largest elevation angle as seen from the radar antenna. This is the point that determines the radar horizon in absence of the wind turbine. Furthermore, a red and orange zone are drawn. When orange and red zones are visible, the radar horizon is diminished by the wind turbine. The red zone indicates the reduction of the radar horizon due to the blades of the wind turbine. The orange zone indicates the reduction of the radar horizon by the mast of the wind turbine. In each figure, flight levels at 5000 ft, 7000 ft and 10000 ft are shown as well.

Note that in the red and orange areas the radar is not completely ‘blind’. The red and orange colours merely indicate where impact of the wind turbines on the radar performance can potentially occur. In these regions the signal from a transponder towards the SSR antenna passes a wind turbine. This means that the wave front of the signal transmitted by the transponder will be disturbed by the wind turbine and does not necessarily mean that the impact on the position estimation of the target by the MSSR is significant.

Figure 4.4 to Figure 4.7 show the line-of-sight as seen from the MSSR towards the existing wind turbines of Boolynaglegagh wind farm. Given that the line-of-sight diagrams are very similar for all wind turbines and no extraordinary cases occur, we show a selection from the set that is representative.

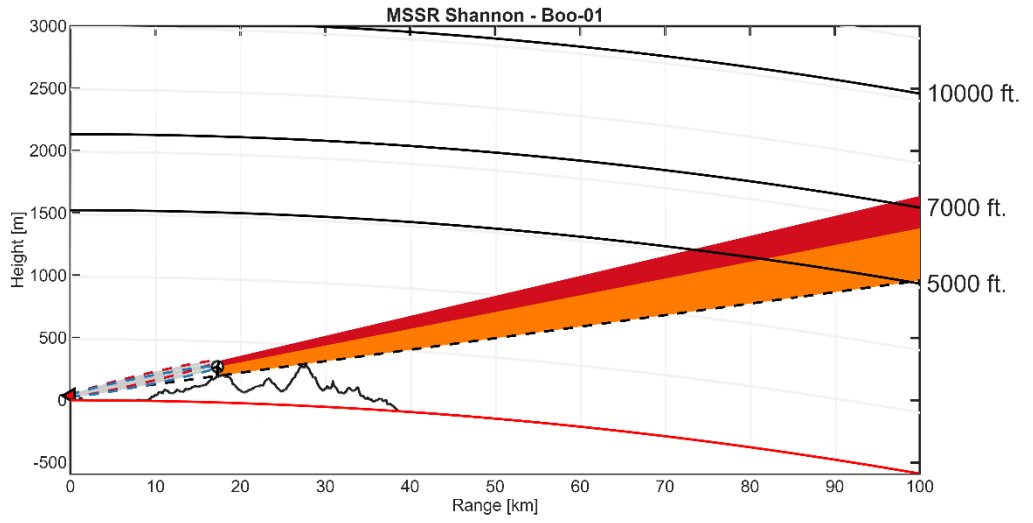


Figure 4.4 Line-of-Sight towards wind turbine Boo-01 as seen from the MSSR.

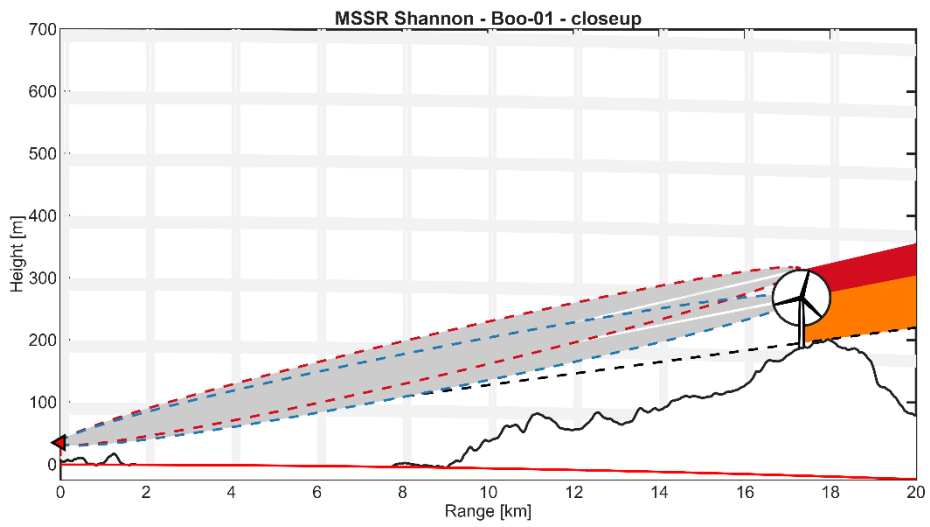


Figure 4.5 Closeup of Line-of-Sight towards wind turbine Boo-01 as seen from the MSSR.

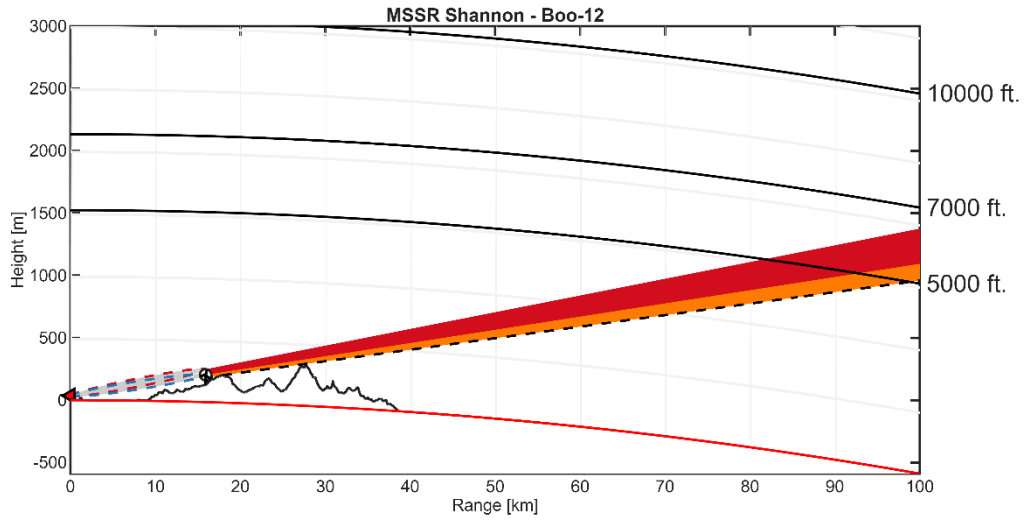


Figure 4.6 Line-of-Sight towards wind turbine Boo-12 as seen from the MSSR.

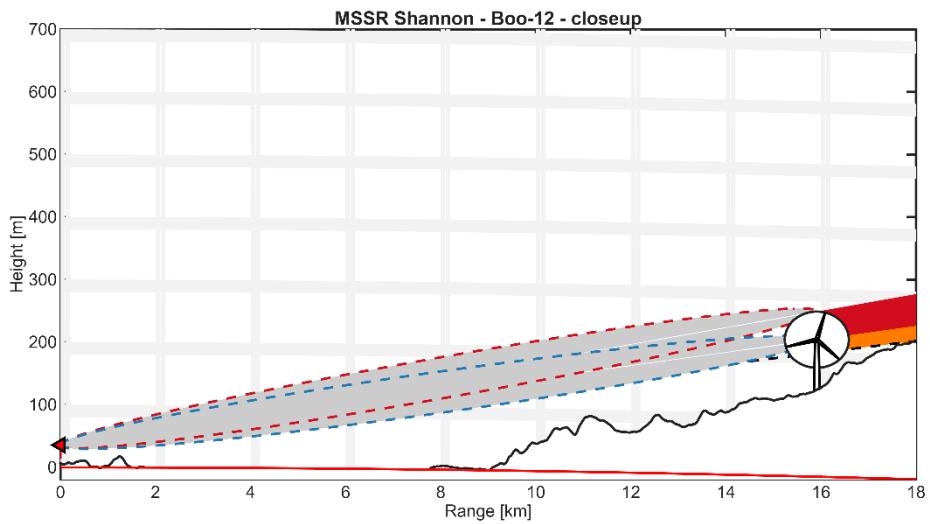


Figure 4.7 Closeup of Line-of-Sight towards wind turbine Boo-12 as seen from the MSSR.

As can be observed from the diagrams, there is full line of sight between the radar and the wind turbines. However, not all turbines will influence the coverage of the radar due to the terrain behind the turbines being taller (as seen from the perspective of the radar).

### 4.3 Line-of-Sight coverage

The results in the previous sections give insight to which extent the wind farm can potentially affect the bearing estimate provided by the MSSR. In this section we show the locations of the affected areas in the Line-of-Sight coverage diagrams or service coverage maps. Coverage diagrams are shown for targets at altitudes of 5000, 7000, 10000 and 35000 ft. A coverage diagram shows whether the performance of the secondary radar can be influenced by the target at a given altitude.

The affected azimuth sector of a single wind turbine is taken as 5° on both sides of the wind turbine, 10° in total. As discussed in Section 2.1 in more detail, outside this +/- 5° sector the impact of the wind turbine on the bearing determination will be smaller than the MSSR bearing accuracy.

The Line-of-Sight coverage diagrams for the MSSR at target heights of 5000, 7000, 10000 and 35000 ft are shown in the figures below. Areas affected by the mast up to the hub height of the wind turbines are shown in orange. Areas affected from hub height up to the tip height are shown in red.

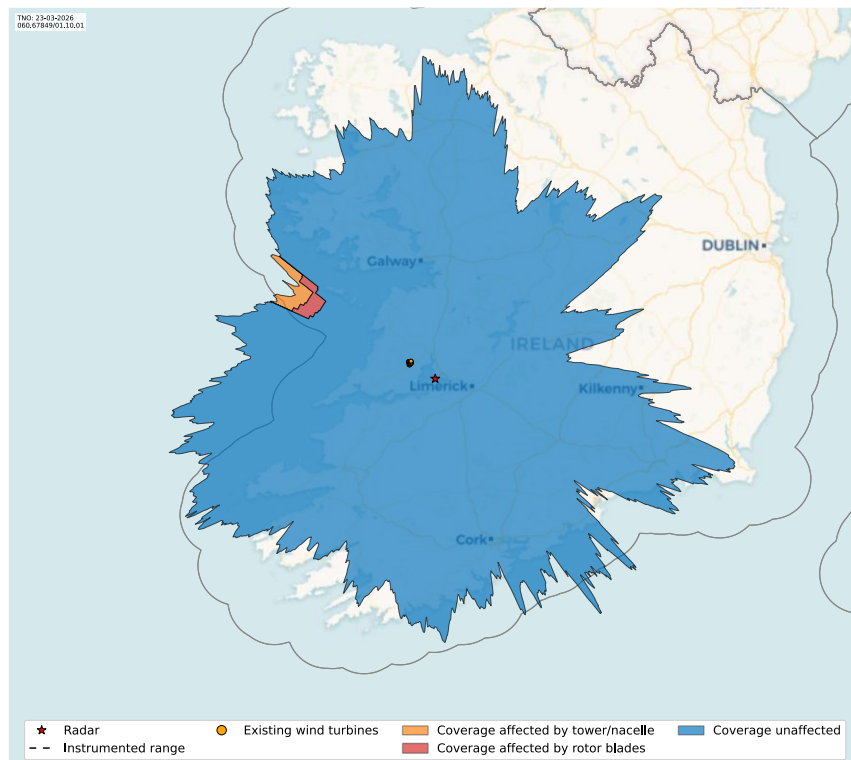


Figure 4.8 Line-of-Sight coverage diagram for a target at 5000 ft AMSL as seen from the MSSR. Only the existing wind turbines of Boolynaglegagh wind farm are considered.

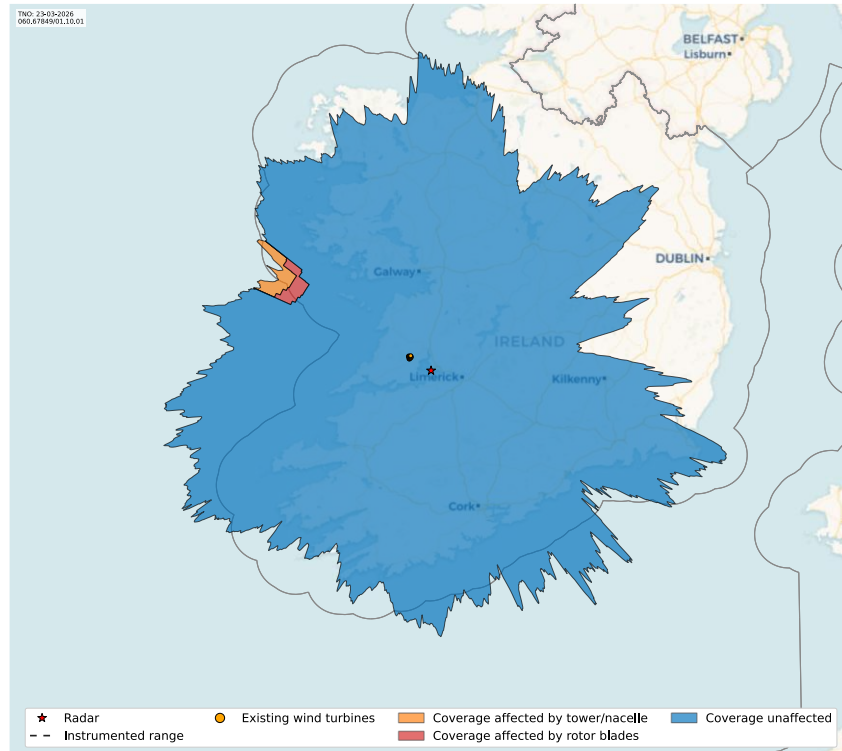


Figure 4.9 Line-of-Sight coverage diagram for a target at 7000 ft AMSL as seen from the MSSR. Only the existing wind turbines of Boolynaglegagh wind farm are considered.

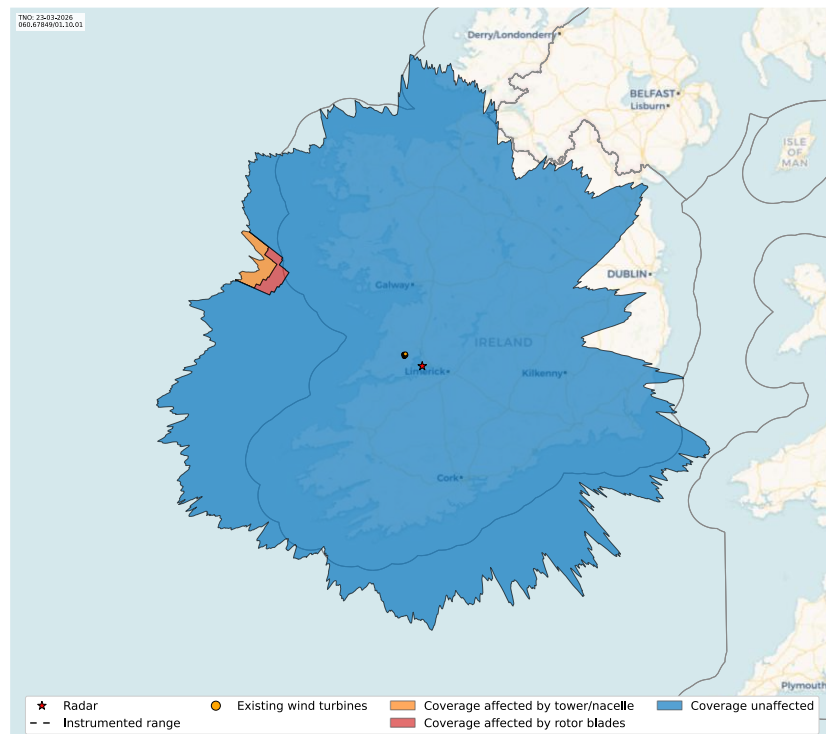


Figure 4.10 Line-of-Sight coverage diagram for a target at 10000 ft AMSL as seen from the MSSR. Only the existing wind turbines of Boolynaglegagh wind farm are considered.

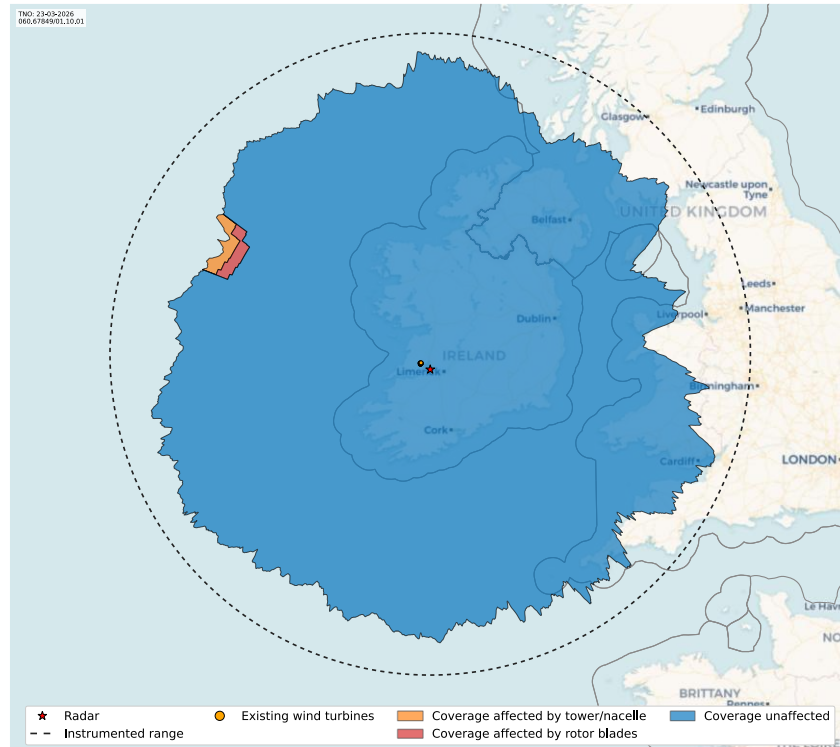


Figure 4.11 Line-of-Sight coverage diagram for a target at 35000 ft AMSL as seen from the MSSR. Only the existing wind turbines of Boolynaglegagh wind farm are considered.

In the figures it can be observed that the wind turbines at Boolynaglegagh result in a zone of potential performance loss at an azimuth range of approximately 297° to 307° as seen from the radar. Moreover, we see that the loss in coverage at all target heights is present only in a small region of the original coverage.

In Table 4.1 we calculate the actual distance in range that is affected by the placement of each individual wind turbine. These values describe the actual kilometre values that relate to the range of the regions of affected coverage that can be seen in the coverage images below for both the nacelle and tower influence and the rotor blade influence regions.

Table 4.1 Change of range in the line-of-sight coverage where the radar’s OBE could be influenced by the tower and nacelle or the blades of the wind turbines at requested altitudes.

Name \ Altitude	Range affected by tower and nacelle [km]				Range affected by rotor blades [km]			
	5000 ft	7000 ft	10000 ft	35000 ft	5000 ft	7000 ft	10000 ft	35000 ft
Boo-01	17.23	19.47	21.66	27.54	25.64	29.33	33.03	43.34
Boo-02	13.89	15.61	17.31	21.70	23.09	26.29	29.51	38.28
Boo-03	16.73	18.89	21.01	26.63	25.24	28.85	32.47	42.49
Boo-04	15.36	17.31	19.23	24.25	24.27	27.69	31.14	40.61
Boo-05	13.16	14.79	16.39	20.53	22.57	25.71	28.86	37.43
Boo-06	15.24	17.16	19.04	23.93	24.56	28.02	31.48	40.96
Boo-07	12.00	13.44	14.84	18.44	21.89	24.85	27.81	35.84
Boo-08	12.98	14.56	16.08	20.05	22.90	26.04	29.17	37.71

Boo-09	13.88	15.61	17.28	21.63	23.67	26.98	30.27	39.28
Boo-10	13.33	14.99	16.60	20.83	22.70	25.87	29.03	37.72
Boo-11	9.97	11.16	12.29	15.18	20.20	22.92	25.60	32.86
Boo-12	6.09	6.77	7.42	9.01	17.14	19.36	21.55	27.39
Boo-13	11.75	13.16	14.55	18.11	21.92	24.92	27.93	36.10
Boo-14	5.49	6.11	6.69	8.06	16.95	19.14	21.29	26.96
Boo-15	20.71	22.77	24.70	29.59	31.48	35.09	38.58	47.81
Boo-16	20.25	22.22	24.11	28.80	30.82	34.30	37.69	46.56

From our quantitative analysis in Table 4.1 we see that there is some range that could be affected by the wind turbine towers and nacelles and by the rotor blades. We should note that the simulation assumes the worst-case scenario where the rotor blade is positioned in the upright position. On average the effect is less due to the rotating nature of the blades.

## 5 Bibliography

- [1] EUROCONTROL, *Guidelines on How to Assess the Potential Impact of Wind Turbines on Surveillance Sensors (EUROCONTROL-GUID-0130)*, 1.2 ed., 2014.
- [2] L. Vinagre and K. Woodbridge, "Secondary surveillance radar monopulse target azimuth error estimation due to obstacle shadowing," in *IEEE Radar Conference. Radar into the Next Millennium (Cat. No.99CH36249)*, Waltham, MA, USA, 1999.
- [3] Ai Bridges Limited, *Radar details with coordinates and heights primary and secondary radars in Ireland*, 2025 November 12.

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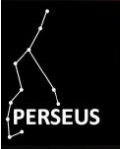
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## Appendix I - Australia MSSR & Wind Farm Case Study

A photograph of several wind turbines silhouetted against a bright sunset sky with orange and yellow clouds. The sun is low on the horizon, creating a lens flare effect.

# Example DEA MSSR Australia due to wind Turbines

Onno van Gent  
04 March 2026



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- 2.0 Background Information - Shadow Effects ..... 5
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- 6.0 Plot Error versus Track Rrror ..... 16
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- 9.0 Conclusions ..... 23

# 1.0 Introduction

- 1.1 In the past TNO performed a DEA for an Australian wind farm developer and investigated the potential effects of a number of wind turbines in the MSSR performance.
- 1.2 As part of the investigation TNO also looked for potential mitigation measures.
- 1.3 The unnamed wind farm comprised over 70 wind turbines and was located near the en-route MSSR from Indra at Mount Bobbara and at a longer distance the combined approach PSR (STAR 2000) and MSSR at Mount Majura, both from Thales near Canberra International Airport.
- 1.4 MSSR is less susceptible to the loss of detection above a wind turbine. A wind turbine may introduce two effects of the MSSR performance :
  - Reduction of the detection range due to the shadow effect of the wind turbine.
  - Angle of arrival measurement errors, also known as Off-Boresight Errors or OBE.

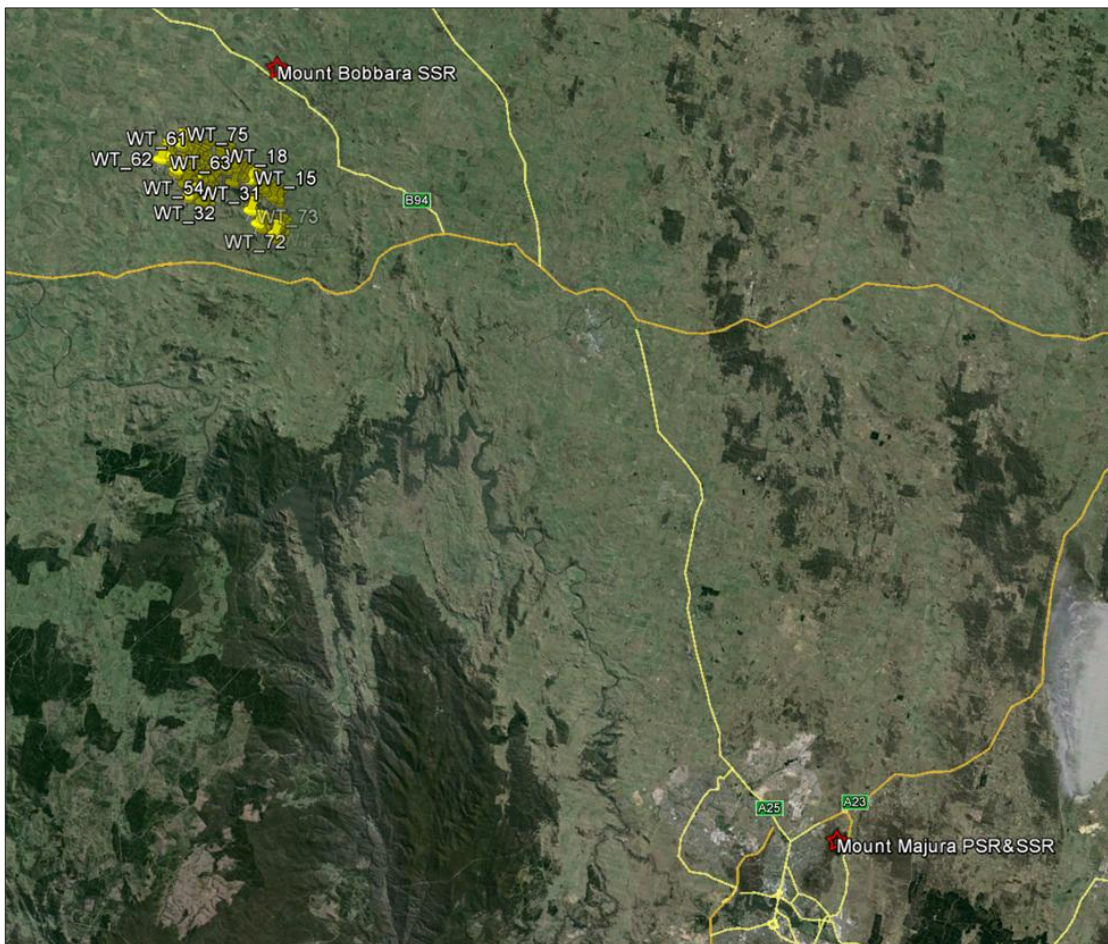


Figure 1 Wind Farm Location in relation to MSSR & PSR



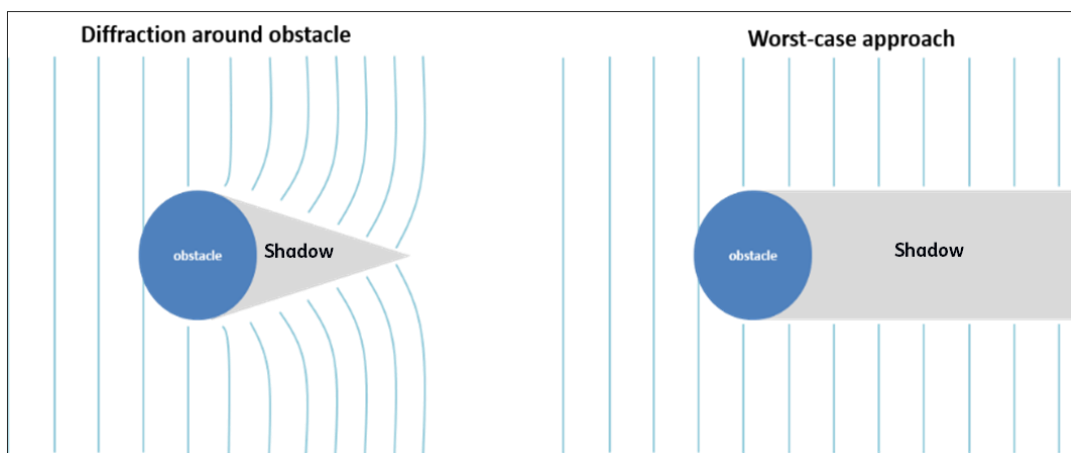
**Figure 2 Mount Majura MSSR & PSR**



**Figure 3 Mount Bobbara MSSR**

## 2.0 Background Information - Shadow Effects

- 2.1 In contradiction to an optical shadow, a wind turbine in the line-of-sight path will affect visibility, but not in all cases will it cause the target to be invisible. Radio waves diffract around an obstacle, limiting the shadow zone directly behind an obstacle. Because energy is reflected back from the wind turbine the presence of a wind turbine will cause a loss in maximum detection range.
- 2.2 However, because the power budget between the transponder and the interrogator is commonly high, detection loss is normally not observed. At maximum range, typically, other MSSRs take over.



**Figure 4 Shadowing**

### Background information – Off Boresight Error

- 2.3 De interrogator of the secondary radar sends a request to the transponder in the aircraft. The transponder replies with a message containing, among others, the flight number and flight height.
- 2.4 The response is received by the antenna. The angle of arrival is determined based on the phase difference over the antenna elements.
- 2.5 Wind turbines within line of sight will interfere and change the wavefront, resulting in the introduction of Off Boresight Errors (OBE) in the bearing measurement.

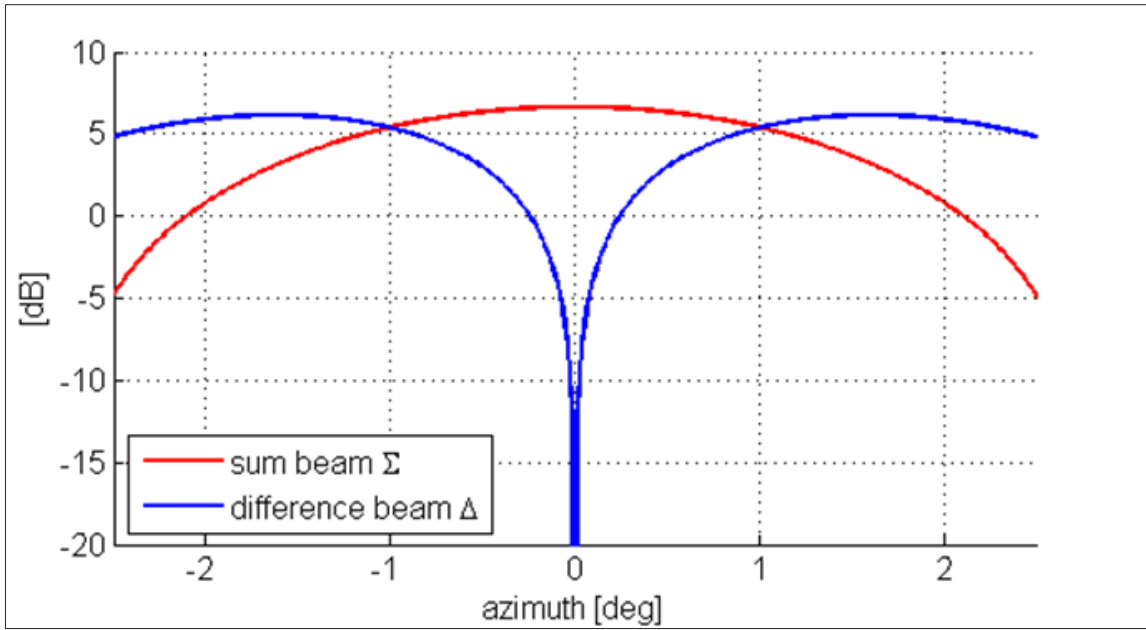


Figure 5

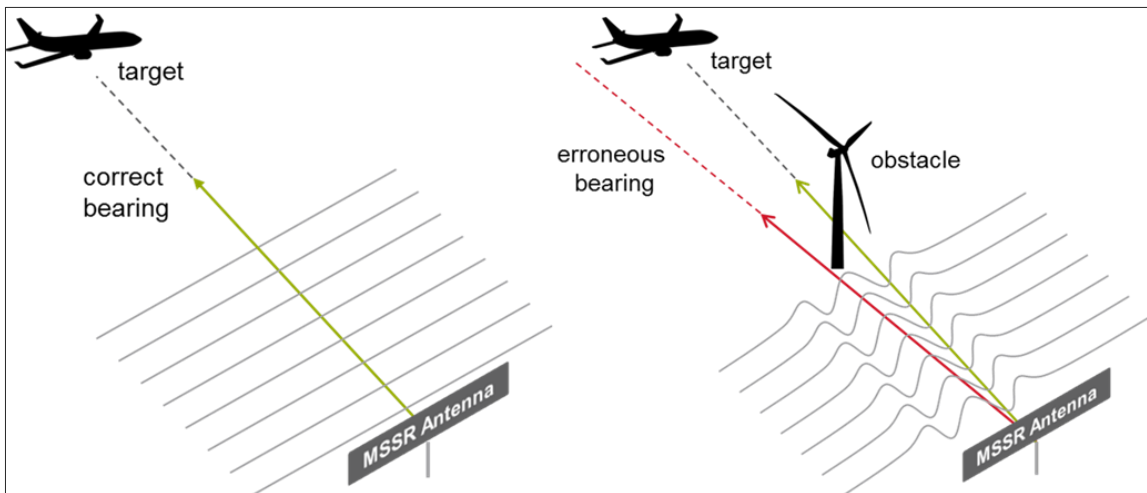


Figure 6

### 3.0 Line-of-Sight Analysis

3.1 First, we determine the line-of-sight between the radar and the wind turbine. In case there is line-of-sight, there will be a potential impact:

- From the radar towards the turbine blade

- From the radar towards the turbine hub

3.2 For the terrain we use the SRTM1 terrain altitude database which has a position resolution of 1 arcsecond and a height resolution of 1 m.

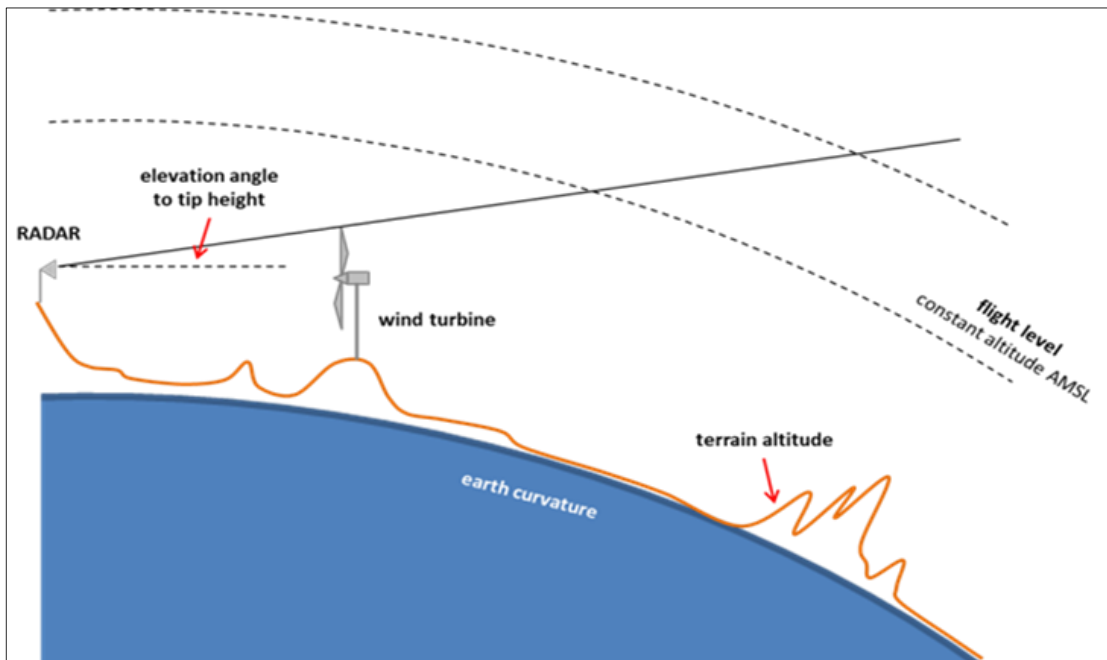


Figure 7

### 4.0 Horizontal View from the Radar:

4.1 Mount Bobbara : The wind farm is located approx. 12 km from the radar.

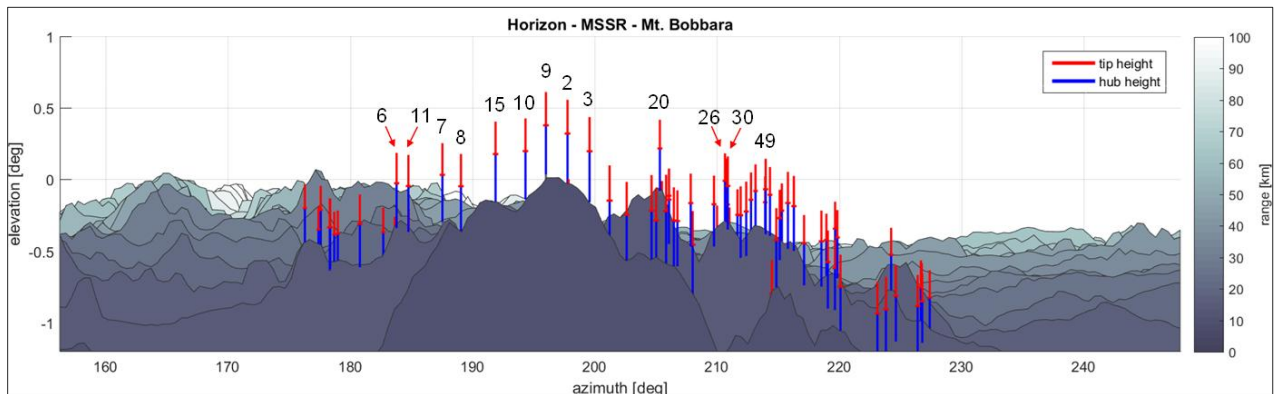


Figure 8

4.2 Mt. Majura : The wind farm is located approx. 80 km from the radar.

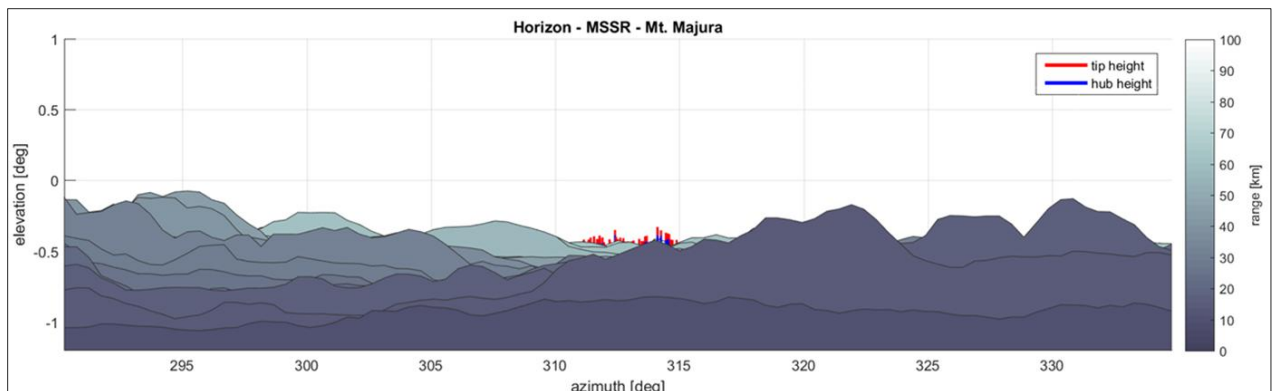


Figure 9

### Line-of-Sight coverage

- 4.3 In the next figures we calculate the horizontal line-of-sight sectors in azimuth where interference of the secondary radar may be caused by the wind turbines.
- 4.4 We discriminate between the zone in which the interference is caused by the mast and nacelle (the orange area) and by the blade positioned in the upright position (the red area).
- 4.5 These calculations are performed at a target height of 3000, 5000, 10000 and 20000 feet.

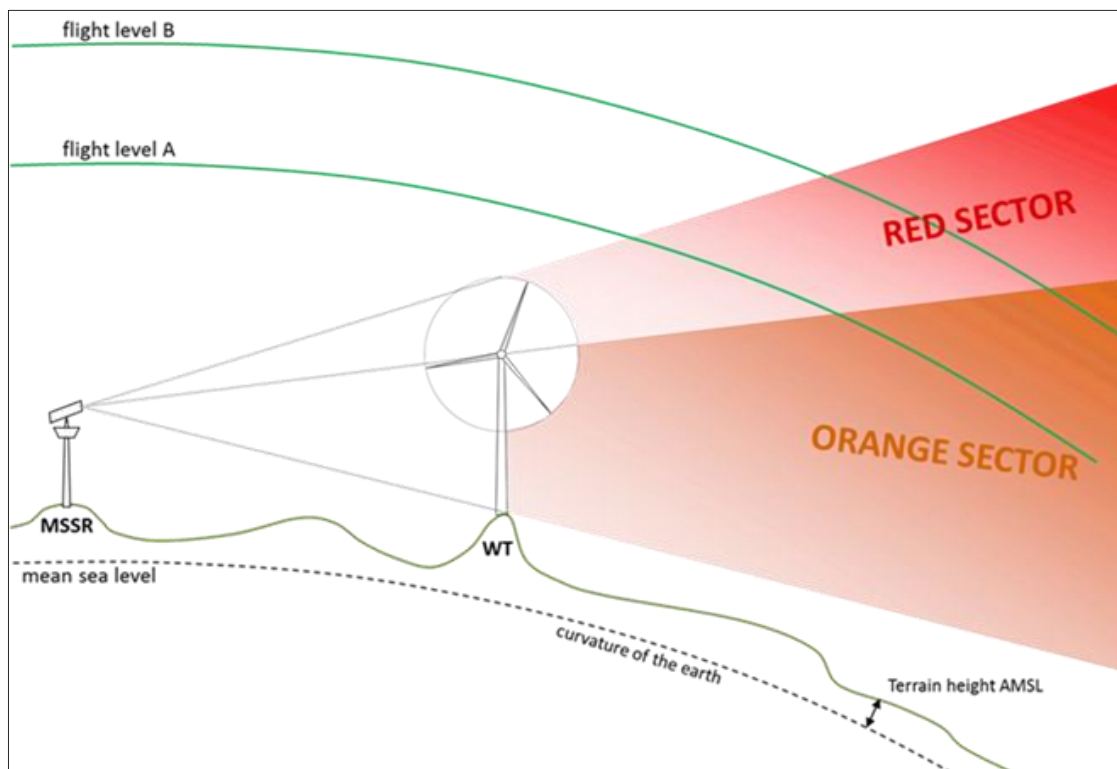


Figure 10

4.6 Mt. Bobbara Line-of-Sight coverage 3000 feet

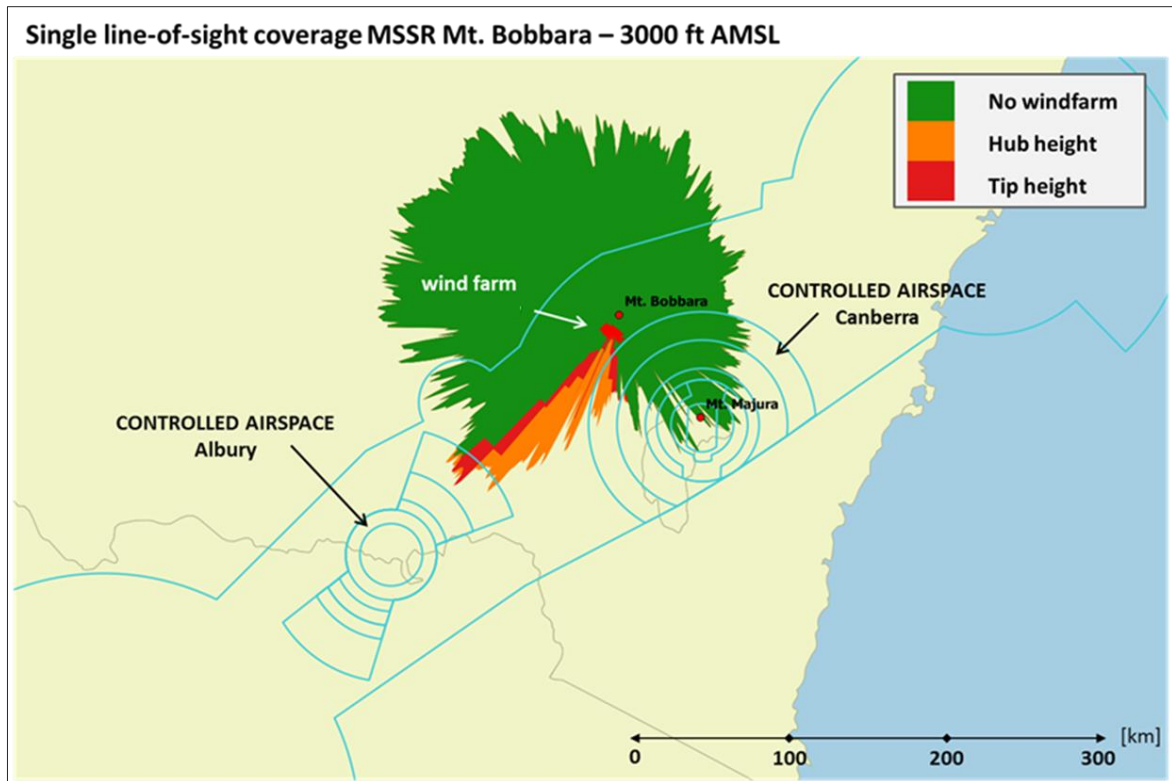


Figure 11

4.7 Mt. Bobbara Line-of-Sight coverage 5000 feet

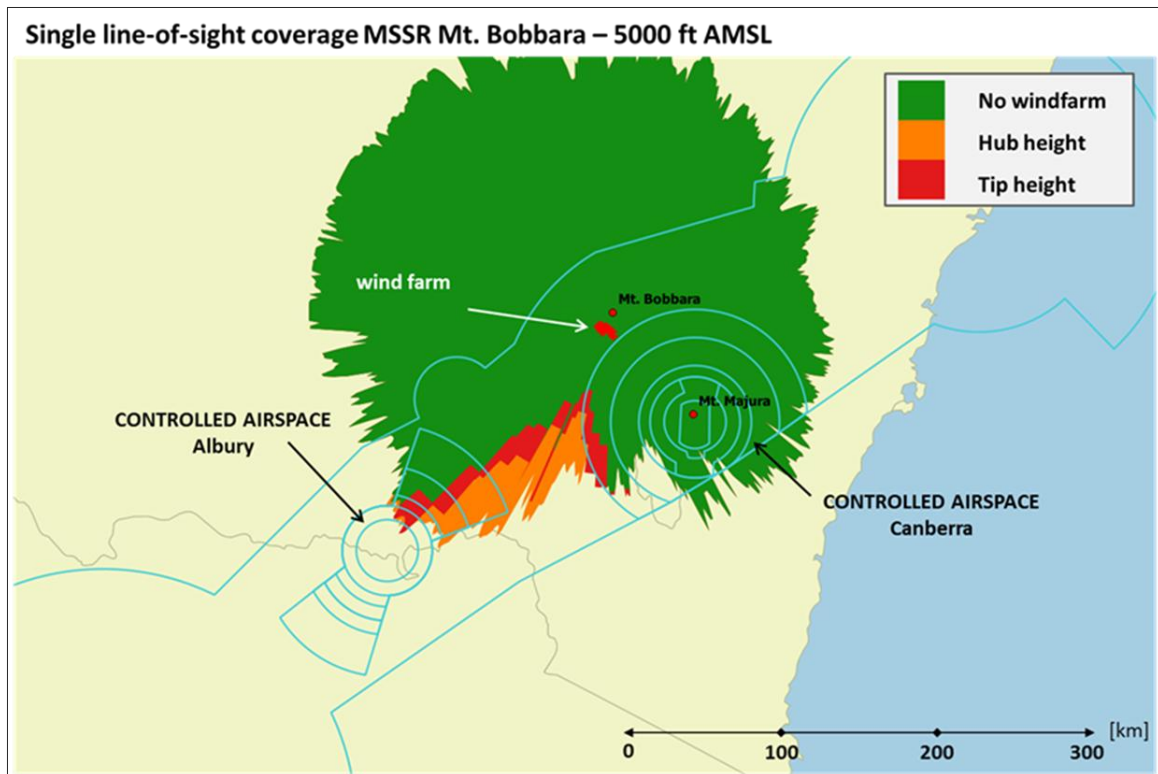


Figure 12

4.8 Mt. Bobbara Line-of-Sight coverage 10000 feet

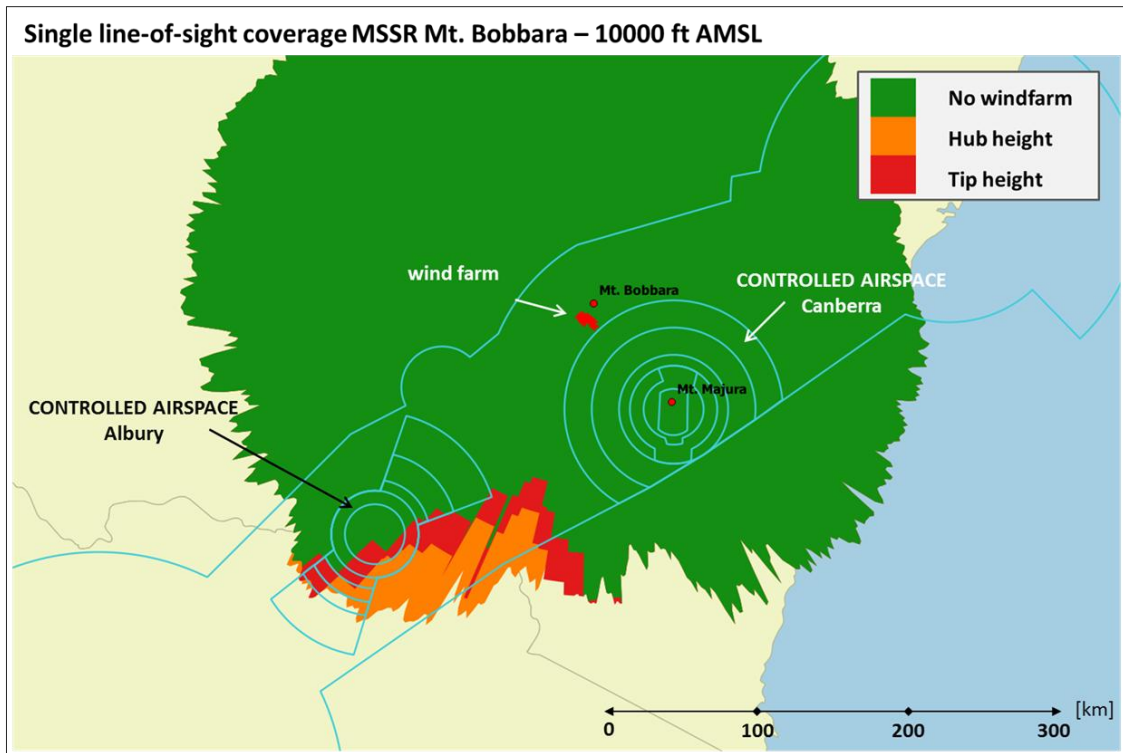


Figure 13

4.9 Mt. Bobbara Line-of-Sight coverage 20000 feet

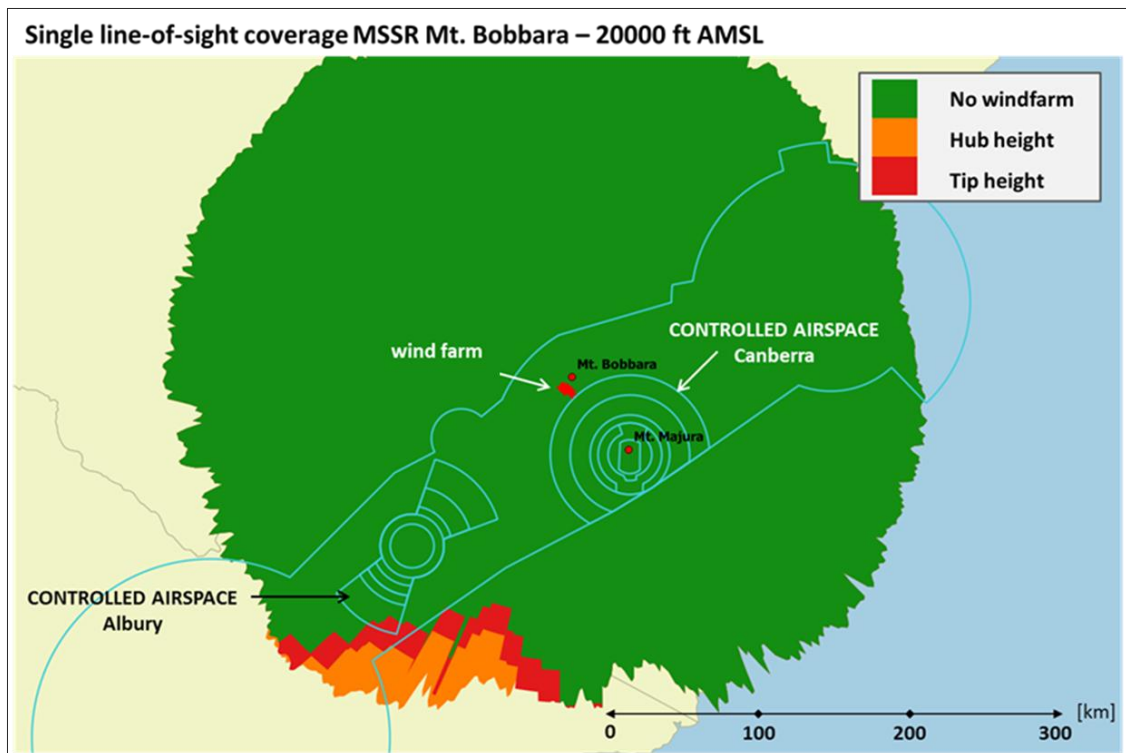


Figure 14

4.10 Mt. Majura Line-of-Sight coverage 3000 feet

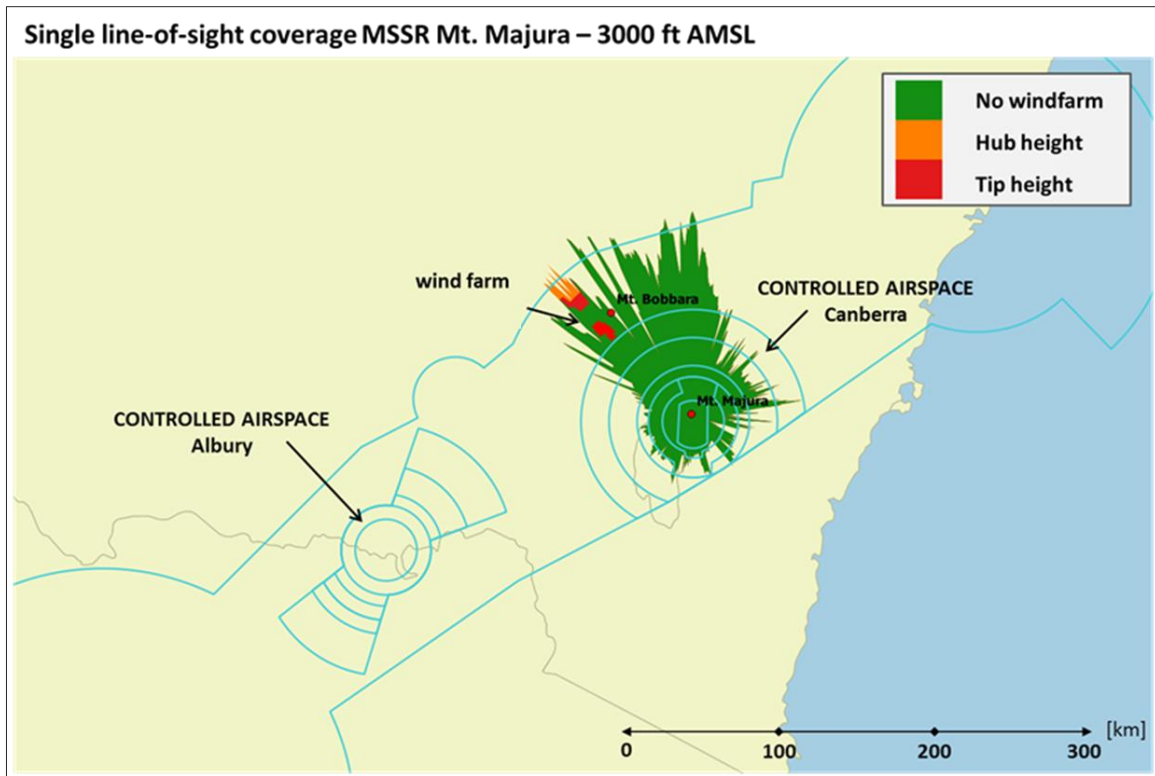


Figure 15

4.11 Mt. Majura Line-of-Sight coverage 5000 feet

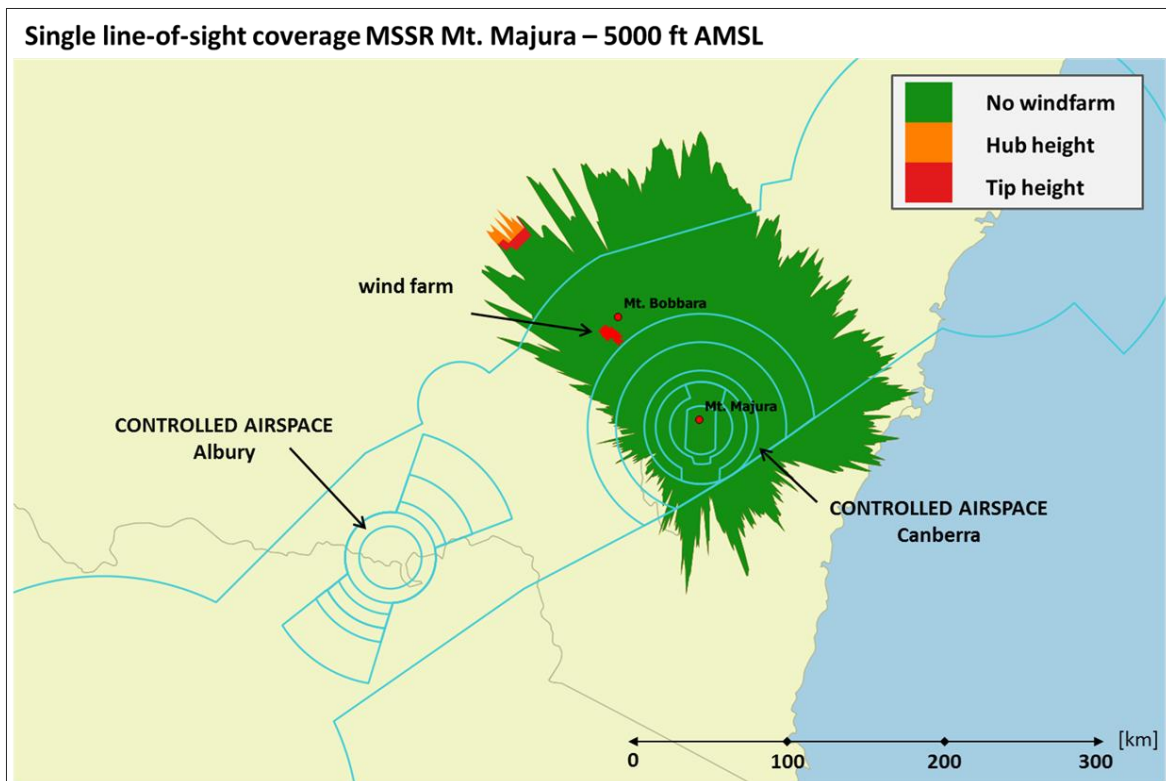


Figure 16

4.12 Mt. Majura Line-of-Sight coverage 10000 feet

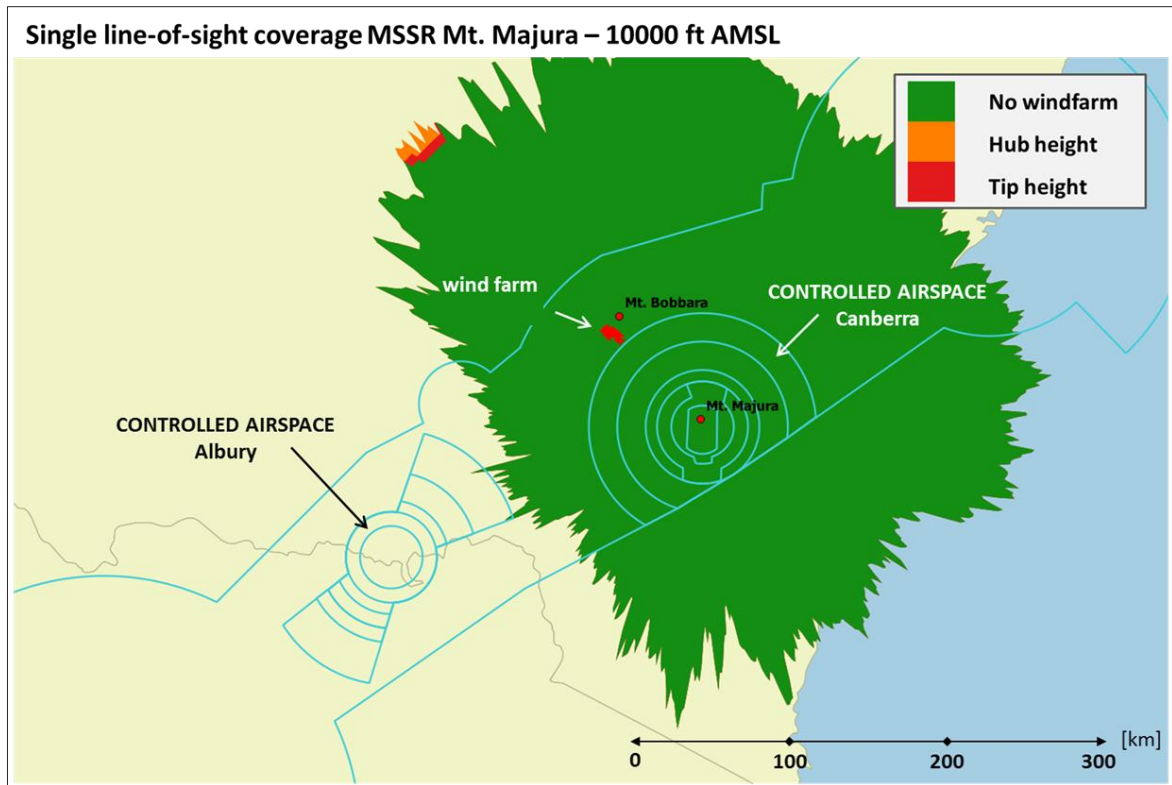


Figure 17

4.13 Mt. Majura Line-of-Sight coverage 20000 feet

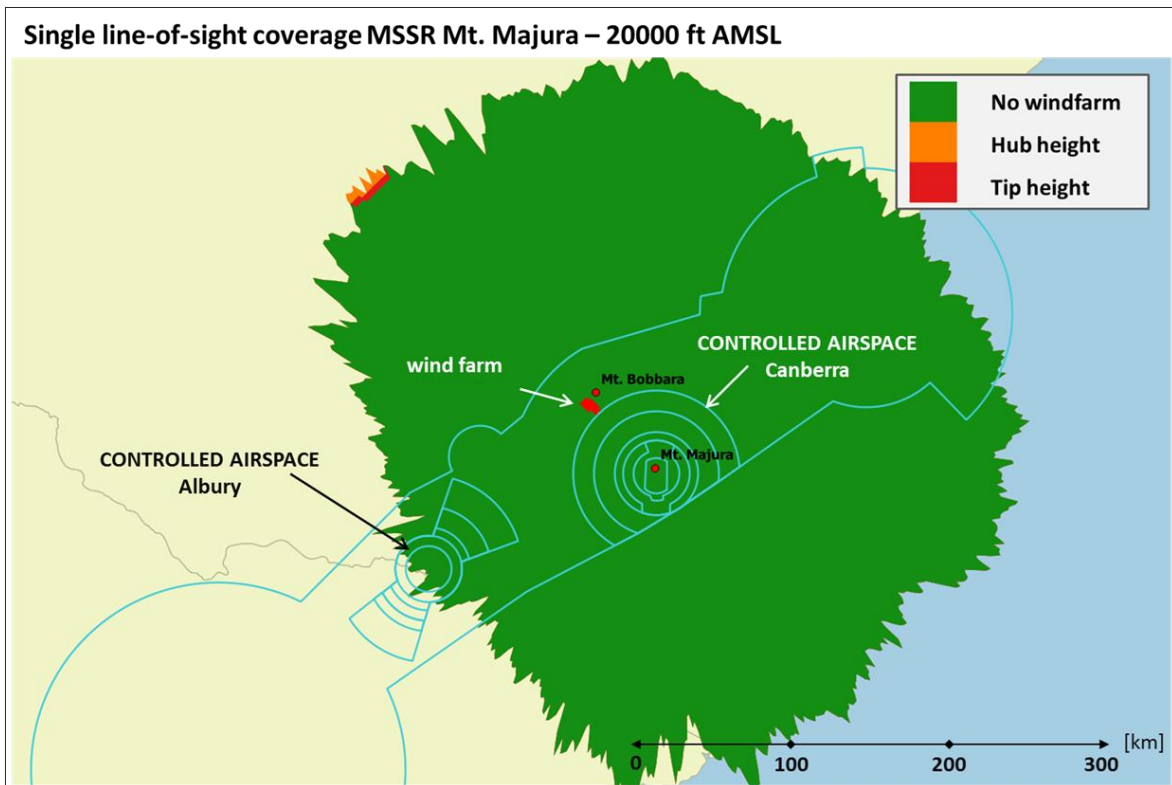


Figure 18

# 5.0 Off-Boresight Errors

- 5.1 The previous results provide an overview of the sectors in elevation and azimuth in which the performance of the secondary radars at Mt. Bobbara and Majura may be influenced by the wind turbines. In this section we calculate the actual azimuth error that may occur.
- 5.2 The amount of interference is calculated with a simulation tool developed by TNO in which the turbines are modelled as infinite cylinders.
- 5.3 The following dimensions are used to determine the diameter of the cylinder:
  - In the orange area from ground to hub, when the mast and nacelle are visible: The average of the length and width of the nacelle.
  - In the red area from hub to tip, when only the blade is visible in the upright position: The length and width of the blade.
  - This approach can be considered as worst-case.
- 5.4 The calculations are performed for different positions of the aircraft and at different orientation of the antenna. In this way a statistical spreading of the azimuth errors can be determined.
- 5.5 The Off-Boresight Error for Mount Bobbara

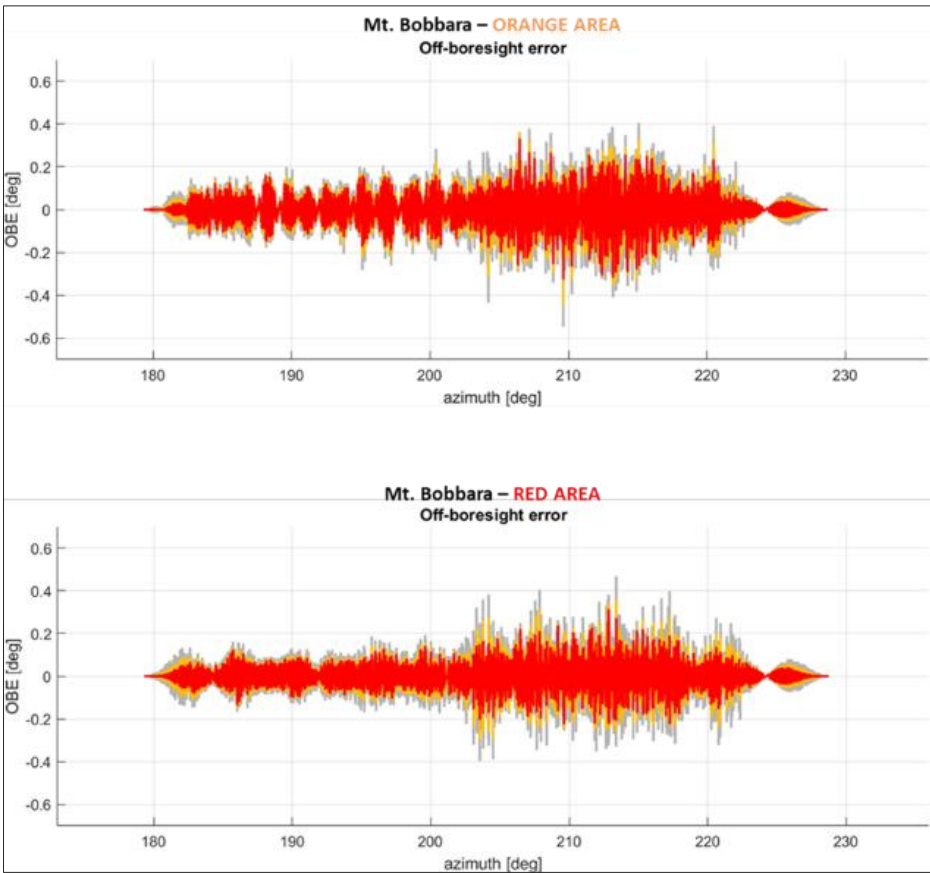


Figure 19

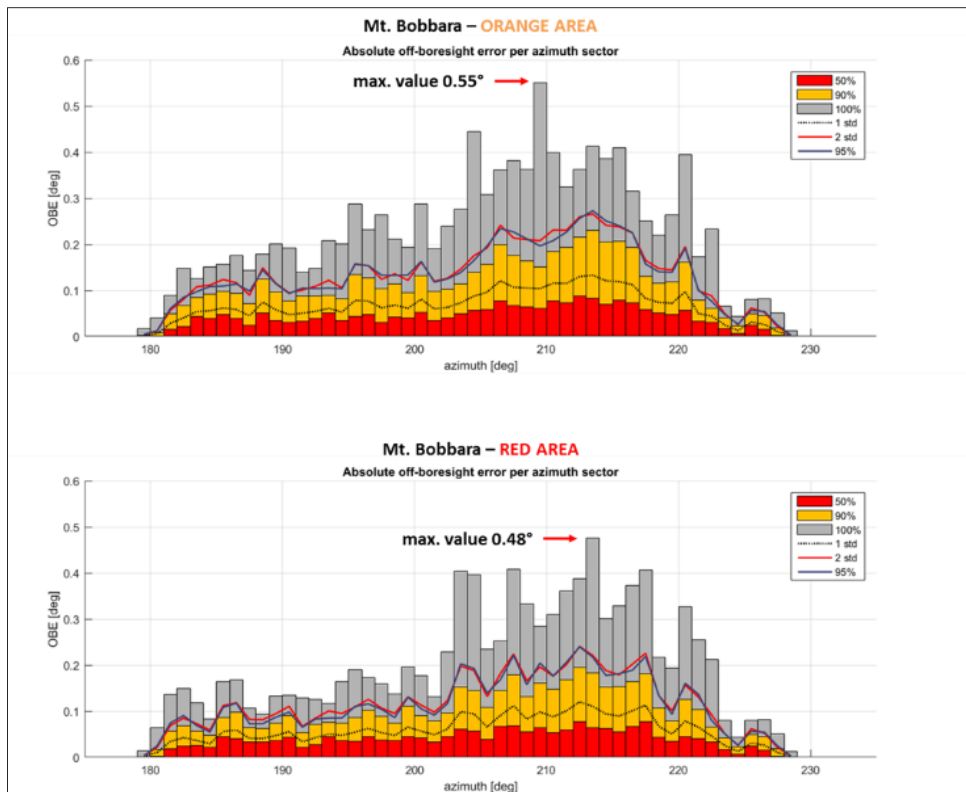


Figure 19

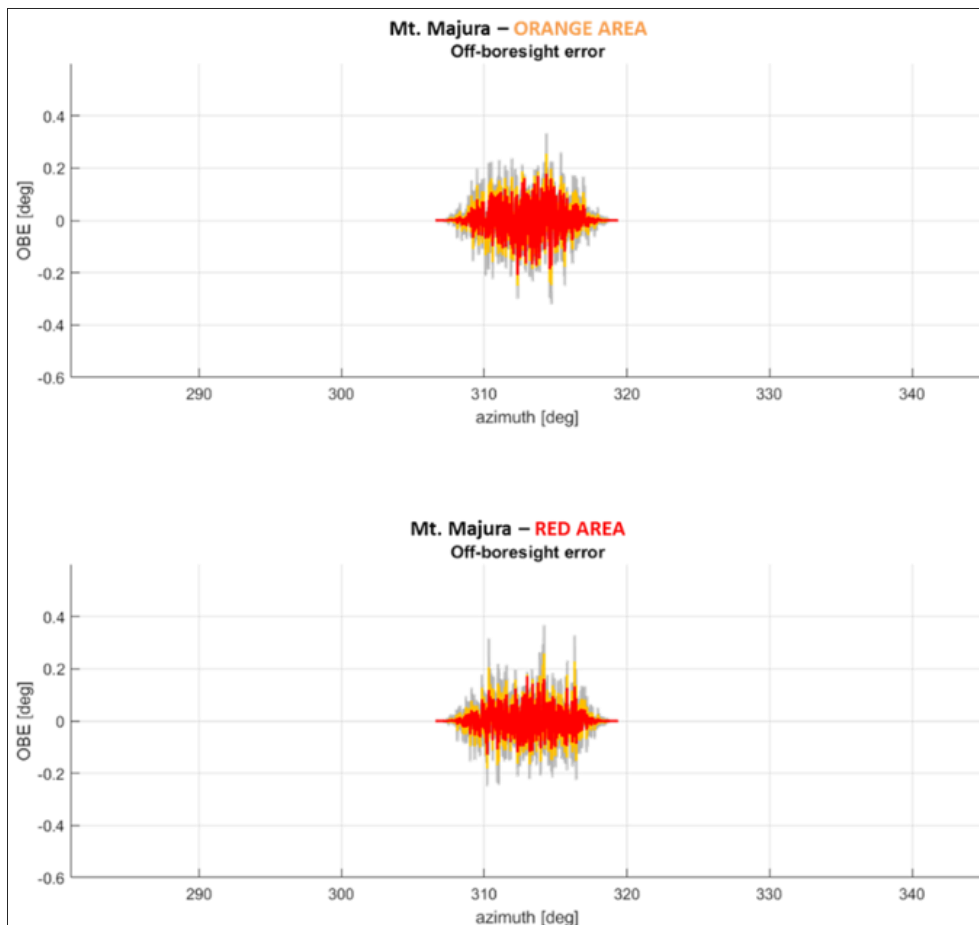


Figure 20

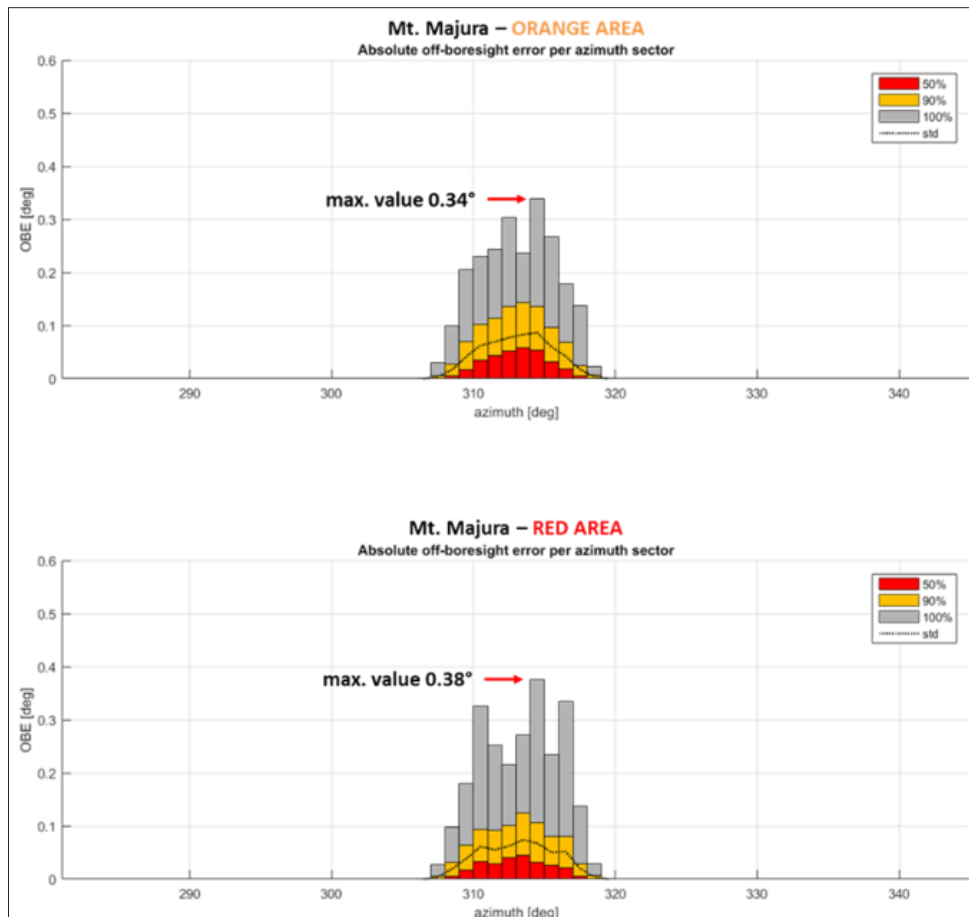


Figure 21 OBE – Mt. Majura

### Cross-range Error Analysis

5.6 The calculation off-boresight angle error results in a cross-range error which is range dependant.

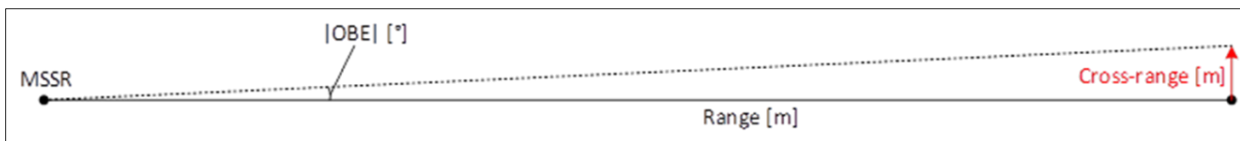


Figure 22

Percentile [%]	OBE [°]	50 km 27 NM	100 km 54 NM	200 km 108 NM	222 km 120 NM	278 km 150 NM
50	0.09	80	160	310	350	440
90	0.23	200	400	800	890	1120
95	0.27	240	470	940	1050	1310
100	0.55	480	960	1920	2130	2670

Figure 23

## 6.0 Plot error versus track error

- 6.1 The errors calculated here represent the bearing error on a single reply of the transponder.
- 6.2 A worst-case assumption is that the measurement error of a single reply is also the measurement error of the plot.
- 6.3 In case a plot is derived from multiple replies, the measurement error of the plot will be less than the measurement of a single reply.
- 6.4 A tracker processes the plot and presents the track update of the target on a computer screen to the operator. In general, the error in the plot is therefore not the same as the error in the track update of the target presented to the operator.
- 6.5 In general, a tracker uses a filter to attenuate errors in the plots. It can, for example, use historic data to predict the next position of the target. It can also use extra available information of the target, like maximum speed and acceleration, to predict the next position.
- 6.6 When the next plot is processed, the track update of the target is a weighted average between the predicted position and the plot position. This way, the error in the plot position is dampened by the tracker.

### Plot Error – Track Error

- 6.7 The blue track (triangles) and plots (squares) show the dampening effect the tracker can have on plot errors.
- 6.8 For the green track, the track updates (triangles) and plots (squares) completely overlap, however.

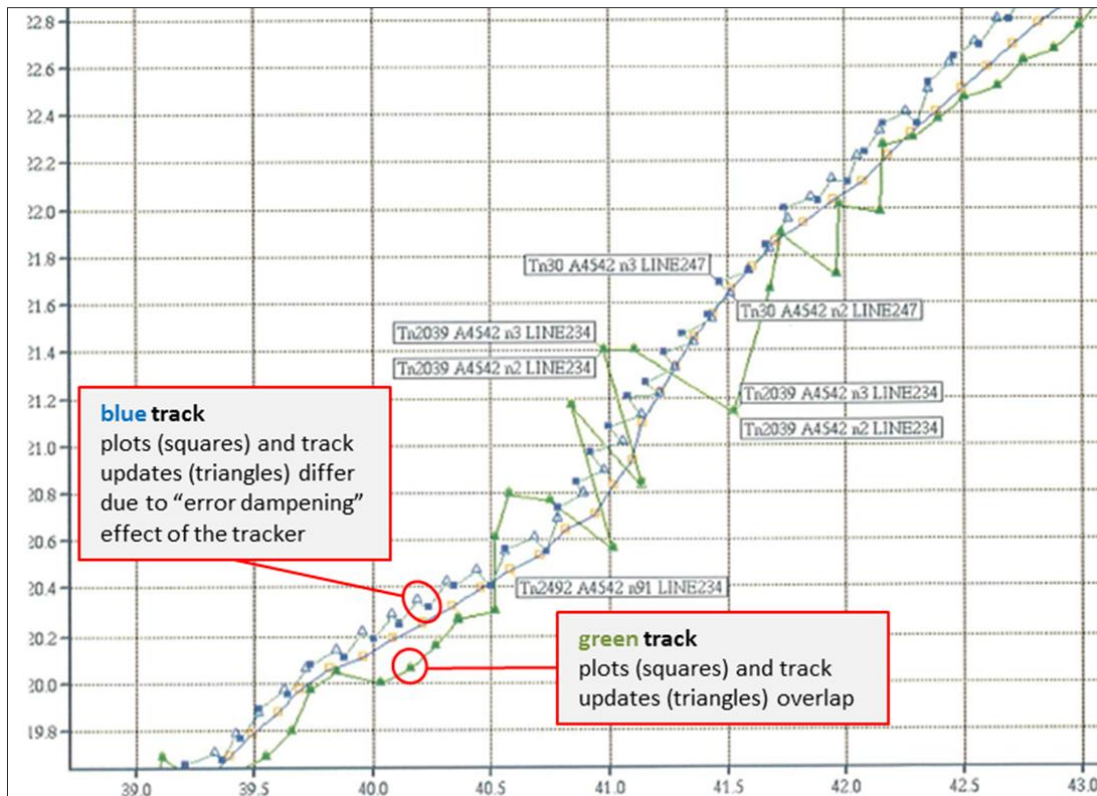


Figure 24

### ASA - Australian ANSP observations

- 6.9 The 95% percentile figure should be applied as starting point.
- 6.10 For each bearing sector, TNO takes the worst-case figure of the red and orange zone.
- 6.11 ASA would like to include the MSSR system error as well. See below (Received from Indra via ASA).

Performance requirement	Value	Comment
Range bias	14 m	Allowed Bias that applies at all ranges.
Range random errors	15 m	1 Standard deviation. Statistical, can assume a Normal Distribution.
Azimuth bias	0.022°	Allowed Bias that applies at all ranges.
Azimuth random errors	0.068°	1 Standard Deviation. Statistical, can assume a Normal Distribution.
Range gain error	1 m/NM	An error in addition to the Range Bias, that increases with the range from the radar. E.g. at 80 NM from the radar a Range bias of 14 m + 80 m = 96 m is allowed. At 150 NM from the radar a Range bias of 14 +150 = 164 m is allowed.

Figure 25

- 6.12 ASA maximum position accuracy requirement for the MSSR at Mount Bobbara measures 0.6 NM with 95% confidence.

## 7.0 Position error calculation

- 7.1 To calculate the total position error, the random errors and bias errors must be treated separately. The random position error is calculated, according to:

$$\sqrt{(\Delta r_{95\%})^2 + (r\Delta\alpha_{95\%})^2 + (rOBE_{95\%})^2}$$

- 7.2 Here  $\Delta r$  indicates the random error in range,  $\Delta\alpha$  the random error in azimuth and OBE the off-boresight error. Note that the errors in azimuth must be multiplied by the range to convert from angle to position. The subscript 95% indicates that all errors are the 95% confidence errors, i.e. two times the standard deviation.

- 7.3 Next, the position bias at each range is calculated according to:

$$\sqrt{\text{bias}(r)^2 + (rRGE)^2 + (r\text{bias}(\alpha))^2}$$

- 7.4 Here  $\text{bias}(r)$  indicates the range bias, RGE the range gain error and  $\text{bias}(\alpha)$  the azimuth bias.

- 7.5 The total position error at range  $r$  is the sum of the random position error and the position bias. Using the above two equations, the maximum range  $r$  at which the total error is equal to 0.6 NM can be determined. This range, calculated for each azimuth sector surrounding the MSSR at Mount Bobbara, constitutes the error contour.

- 7.6 *Note that the line does not extend to the full instrumented range of the MSSR of 256 NM. Following the range error requirements of the table on the previous sheet, thus without the wind turbines, the range at which the position error exceeds the 0.6 NM (95% confidence) is approximately 195 NM, or 360 km!*



**Figure 26 Mt. Bobbara Error contour**

## Combining Line-of-Sight coverage and error contour

7.7 Now that we have a clear picture of the area where the ASA requirement for mount Bobbara is met, it makes sense to combine the error contour with the line-of-sight coverage diagrams at various altitudes.

7.8 The hatched area shows the zone where the minimum requirement of ASA is not met.

7.9 The following conclusions can be drawn:

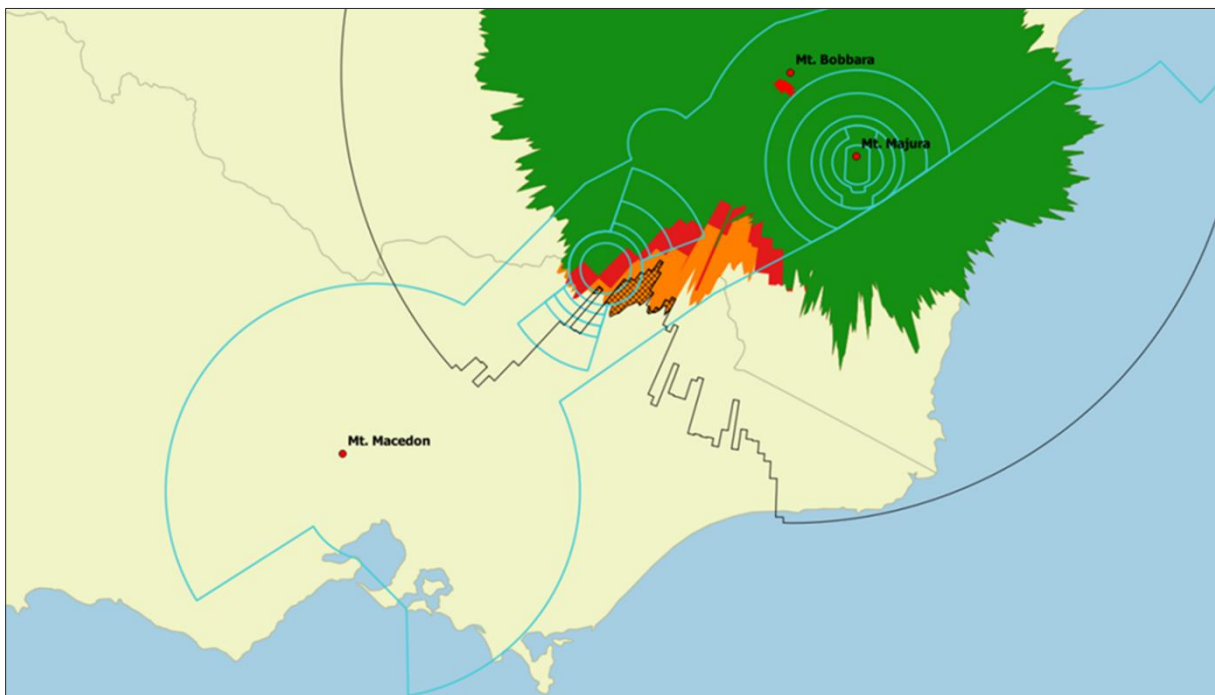
- The altitude 8000 ft is the lowest of the calculated altitudes in this report at which the error contour and line-of-sight coverage overlap.

- This means that at an altitude 5000 ft or lower the position error in the affected areas is less than 0.6 NM.

- At altitudes between 5000 ft and 8000 ft, some overlap (shaded area) between the line-of-sight coverage, and the error contour will exist.

- At an altitude of 10000 ft there is significant overlap between the error contour and the line-of-sight coverage (shaded area). In this area the position requirement of 0.6 NM is not met. However, for the major part of the affected (orange and red) areas the position error will be less than the required 0.6 NM.

- At an altitude of 20000 ft the position error requirement is not met in almost the entire affected area.



**Figure 27 – Mt. Bobbara Combined Los & Error contour 8000 ft**

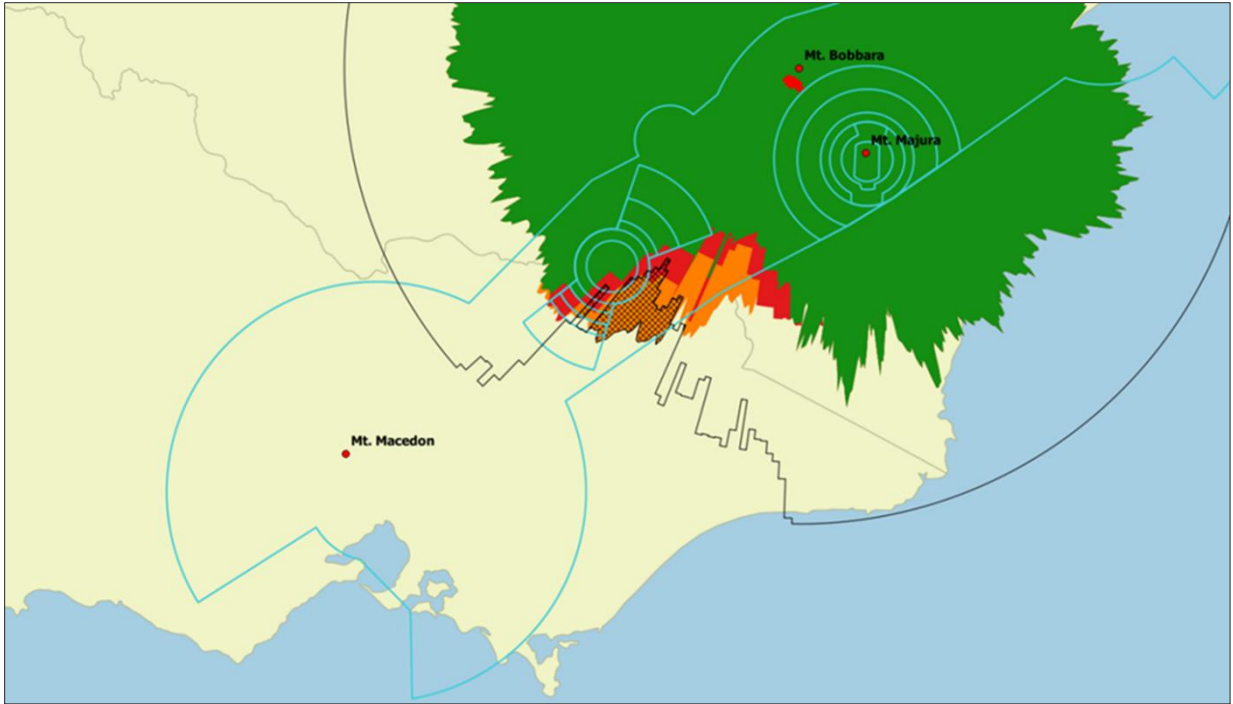


Figure 28 – Mt. Bobbara Combined Los & Error contour 10000 ft

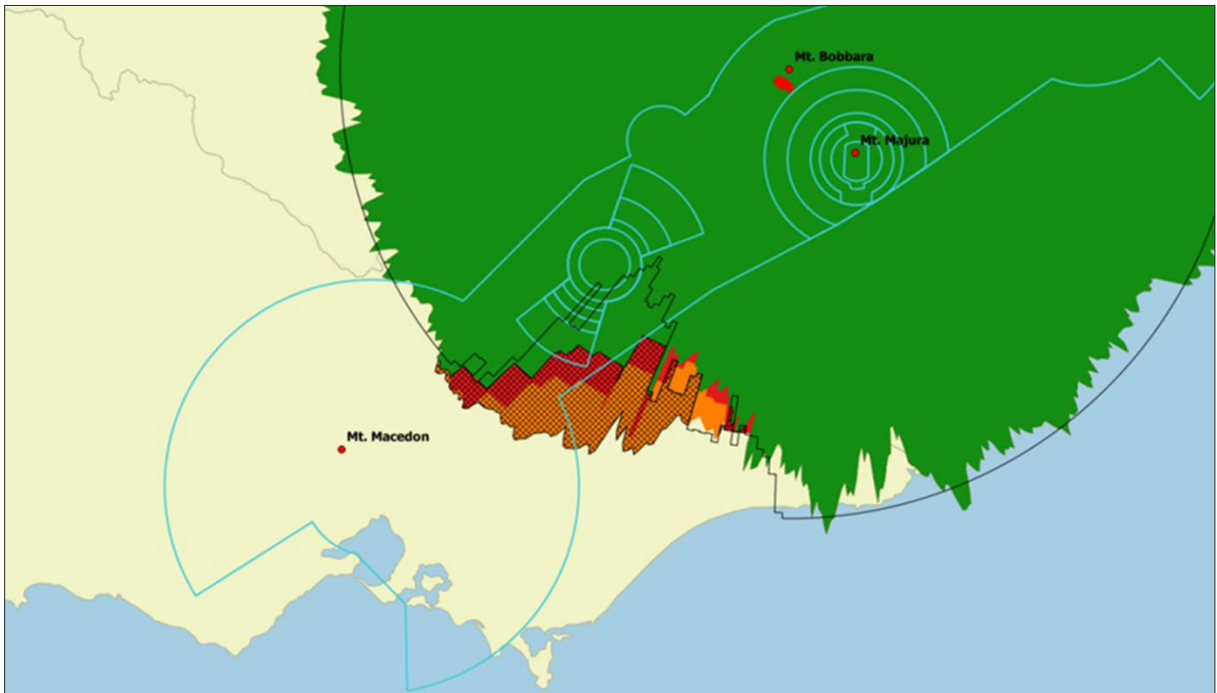


Figure 29 - Mt. Bobbara Combined Los & Error contour 20000 ft

# 8.0 Potential Mitigation Measure

- 8.1 Combining or fusing track and plot data from multiple MSSRs.
- 8.2 In this case from Mount Bobbara, Majura, and another already existing en-route MSSR at Mount Macedon.



Figure 30

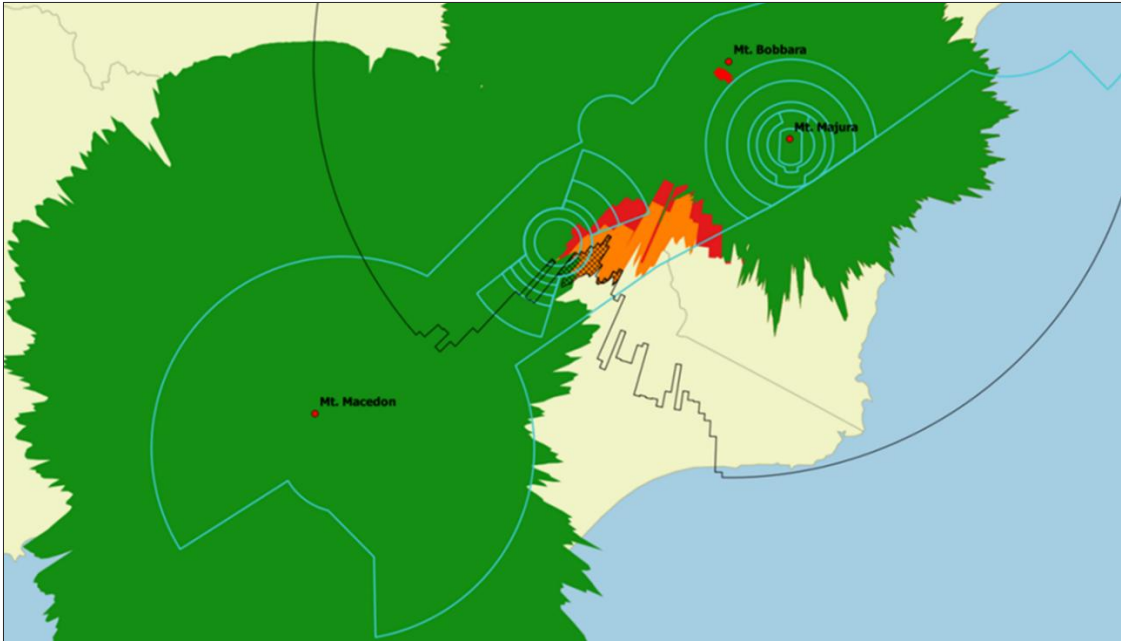


Figure 31 – Combined Mt. Bobbara Majura and Macedon 8000 ft

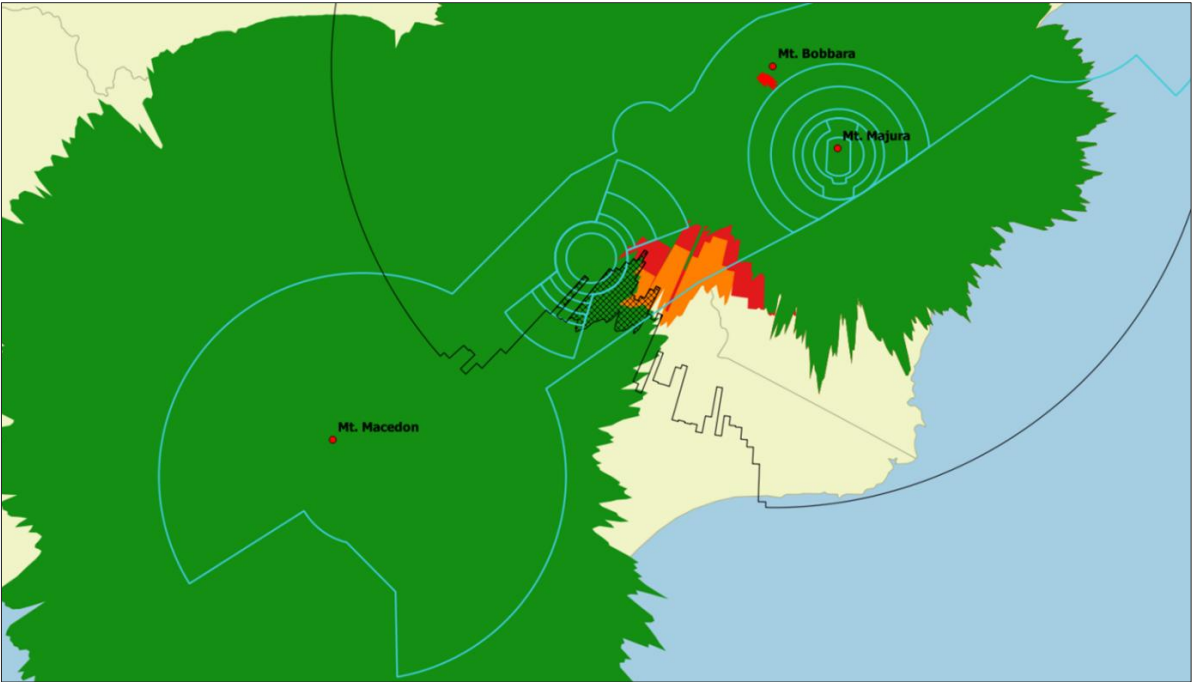


Figure 32 – Combined Mt. Bobbara Majura and Macedon 10000 ft



Figure 33 - Combined Mt. Bobbara Majura and Macedon 20000 ft

## 9.0 Conclusions

- 9.1 The previous figures demonstrate that, the region where the positional error requirement for Bobbara MSSR is not met, is partly covered by Mount Macedon MSSR at 8000 ft and 10000 ft. At 20000 ft Mount Macedon fully covers the affected area.

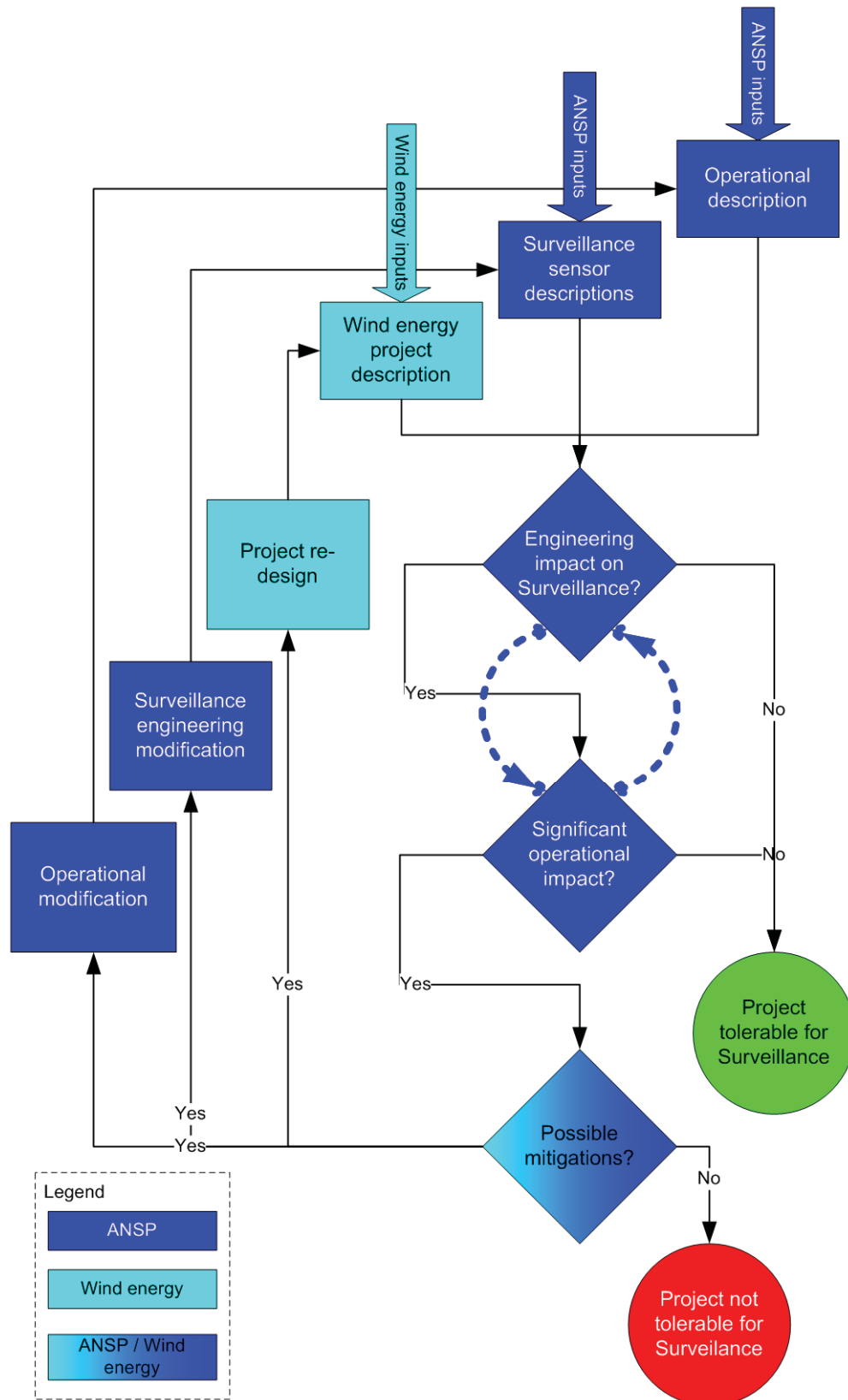
Appendix J - Eurocontrol Guidelines

## 2. Impact assessment process

Figure 1 describes the generic process to be followed by ANSP and the wind energy developers when assessing the impact of a wind turbine project on surveillance infrastructure. This diagram has deliberately been kept at a high level to be compatible with formal and informal requests.

Wind energy developers are invited to initiate this process on the basis of these guidelines as soon as possible in the preparation phase of their project. At the earliest stages of the project, when there is more room for adaptation, it is anticipated that cost effective mitigation options (see section 4.6 for some possible mitigations) could be agreed; whereas at later stages, viable mitigation options could be more difficult to define and to agree on.

In order to facilitate this dialogue, it is recommended that ATM stakeholders (e.g. ANSP, NSA) publish a single point of contact (e.g. a generic email address) through whom initial contact can be established.



**Figure 1: Impact Assessment Process**

On Figure 1 the activities have been allocated on the basis of a formal request. In theory any activity can be undertaken by anybody provided that they have all the required pieces of information and the relevant knowledge.

## 2.1 Wind energy project description

This is a wind energy developer activity; it consists of collecting all the relevant wind energy project information to perform an impact assessment on the proposed development.

The information to be provided is described further in Section 3.1.

This project description shall be provided with any formal request to get a formal advice from the ANSP. It is to be noted that this process only addresses the impact on surveillance infrastructure, whereas the project may have other impacts that the ANSP have to assess. It is also to be noted that formal requests will be governed by state policy and as such will have to respect a number of national rules.

This project description may also be provided through an informal request at the earliest possible stage to avoid any further nugatory works. This is typically an informal approach to gauge reaction to a new development which is still at the exploratory stage of design. This should be encouraged, as early changes to a development proposal, prior to formal submission to the planning authorities, are much easier to introduce to meet the needs of the ANSP.

By whatever route notification is received, it is important that as much of the relevant information is included as possible. At a pre-planning stage precise details of turbine locations and dimensions are often not fixed therefore any results based on this incomplete information must obviously be caveated such that relevant decision making authorities treat them with caution. Any change in the design proposal will require a re-assessment.

## 2.2 Surveillance sensor description

This is an ANSP activity; it consists of collecting all the relevant surveillance sensor information to perform an impact assessment on the proposed development.

In case the sensor is associated to a Far-Field Monitor (FFM), information related to that FFM is also needed.

The information to be provided is described further in Section 3.2.

This surveillance sensor description shall, subject to appropriate security and confidentiality considerations, be made available on request for preliminary analysis or site selection to wind energy developer.

## 2.3 Operational description

This is an ANSP activity; it consists of collecting all the relevant operational information (e.g. aeronautical navigation routes) to perform an impact assessment on the proposed development.

The information to be provided is described further in Section 3.3.

This operational description may, subject to appropriate security and confidentiality considerations, be made available on request for preliminary analysis or site selection to wind energy developer.

This operational description shall, subject to appropriate security and confidentiality considerations, be made available in response to a formal request attributable to a specific planning application

## 2.4 Engineering impact on surveillance

This is an ANSP activity, which consists of assessing the potential performance impacts that the submitted wind energy project could have on individual surveillance sensors operated by the ANSP, to derive the impact it may create at the output of the surveillance system and to consider possible mitigation mechanisms that could be introduced.

The assessment is described further for each type of radar in Chapter 4.

Although it is recognised that in most cases the sensor outputs will not be provided directly to the Air Traffic Controllers, but will go through further processing stages like Surveillance Data Processing systems; there are still some cases where the sensor output is used operationally (in normal or in fall-back mode). Therefore the maximum effort should be undertaken to minimise the impact of wind turbines at the earliest stages of the surveillance chain i.e. at the surveillance sensor level.

The application of specific features at surveillance data processing level is considered as a possible mitigation. Further mitigation possibilities may also be considered – a range of these are identified in section 4.6.

At this stage, the methodology encourages an ANSP engineering department to initiate discussions with the operational staff (as shown with the curved arrows on Figure 1) to assess the potential technical and operational impacts of the wind energy project in order to identify realistic mitigation measures that, in general, have both engineering and operational implementation aspects.

## 2.5 Operational impact on surveillance

This is an ANSP activity, which consists of assessing the impacts that the submitted wind energy project could have on the ANSP operations based on surveillance services and/or on the surveillance data service the ANSP is providing to other users.

This activity is described further for each type of radar in Chapter 4.

It is to be remembered that an ANSP is held legally accountable for the safe provision of service at all times.

As stated in paragraph 2.4 above and although the engineering and operational impact assessment stages are shown as two different boxes on Figure 1, a strong cooperation between the operational and engineering departments of the ANSP is needed to ensure that all aspects have been analysed and that all possible mitigations have been identified.

## 2.6 Possible mitigations

This is a combined ANSP/wind energy developer activity, which consists of identifying potential modifications to the surveillance system **and/or** the operational environment **and/or** the wind energy project that could mitigate to a tolerable level the impact of the wind energy development project.

This activity should be based on a transparent, coordinated and balanced approach with the objective of finding a solution that can be agreed by all parties.

When assessing mitigation options the following criteria shall be taken into account:

- Air traffic safety is maintained
- Cost efficiency based on through life cost over an agreed time period

The detailed assessment required to judge the suitability of such mitigations is beyond the scope of these guidelines due to their site specific nature.

## 2.7 Project re-design

This is a wind energy developer activity, which consists of taking into account in his project the possible mitigations identified at the previous stage to make the project impacts tolerable.

## **2.8 Surveillance engineering modification**

This is an ANSP activity, which consists of taking into account the possible mitigations identified at the previous stage and that are applicable to the surveillance system to make the project impacts tolerable.

It is desirable that any surveillance engineering modification should be carbon neutral and have no detrimental impact on the environment.

## **2.9 Operational modification**

This is an ANSP activity, which consists of taking into account the possible mitigations proposed at the previous stage and that are applicable to the operational environment to make the project impacts tolerable.

It is desirable that any operational modification should be carbon neutral and have no detrimental impact on the environment (e.g. noise, longer routes, etc.).

## **2.10 Feedback to surveillance sensor manufacturers**

The ANSP should feedback to the surveillance sensor manufacturer the observed impacts of wind turbines on the sensor behaviour so that the manufacturer can improve its sensor design to be less sensitive to wind turbines.

## Appendix K - NLD Experience on Wind Turbine Impacts on Radars

# NLD EXPERIENCE ON WIND TURBINES IMPACT TO RADARS ONNO VAN GENT

13 November 2025



# › PERSEUS DEVELOPMENT AT TNO

## MORE THAN 25 YEARS OF EXPERIENCE

- › Defence Research Laboratory established at Waalsdorpervlakte, The Hague before WW2.
- › In 1982 Defence Research merged into TNO organisation
- › TNO is a not-for-profit organisation established by law
- › Since 1995 TNO investigates the effects of wind turbines on Defence radars and develops assessment methods.
- › Most recent method is PERSEUS, sponsored by Ministry of Defence as well as Ministry of Infrastructure and Environment.



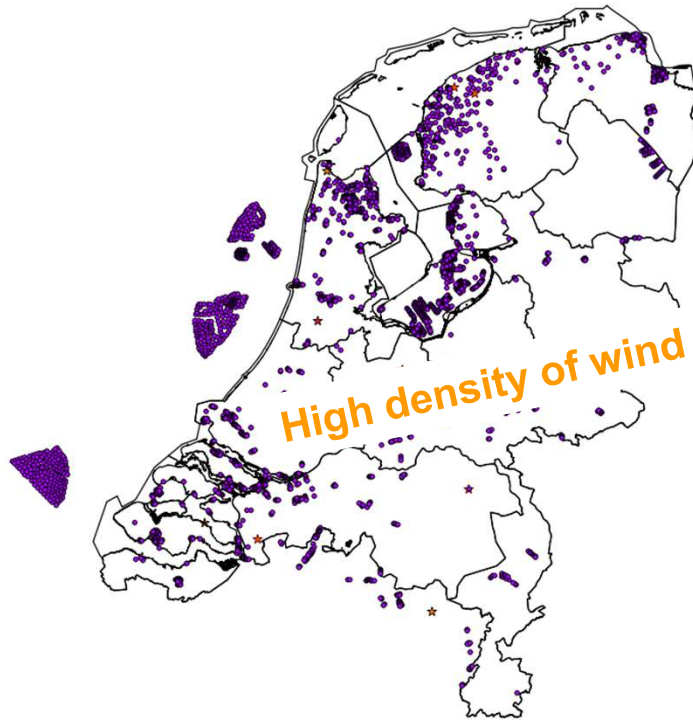
## › CONTENT

- › Dutch regulations
- › Main features PERSEUS radar performance modelling
- › Some examples of mitigation measures
- › Complementary tooling for secondary radar (IFF)



# SITUATION IN THE NETHERLANDS

More than 5000 wind turbines



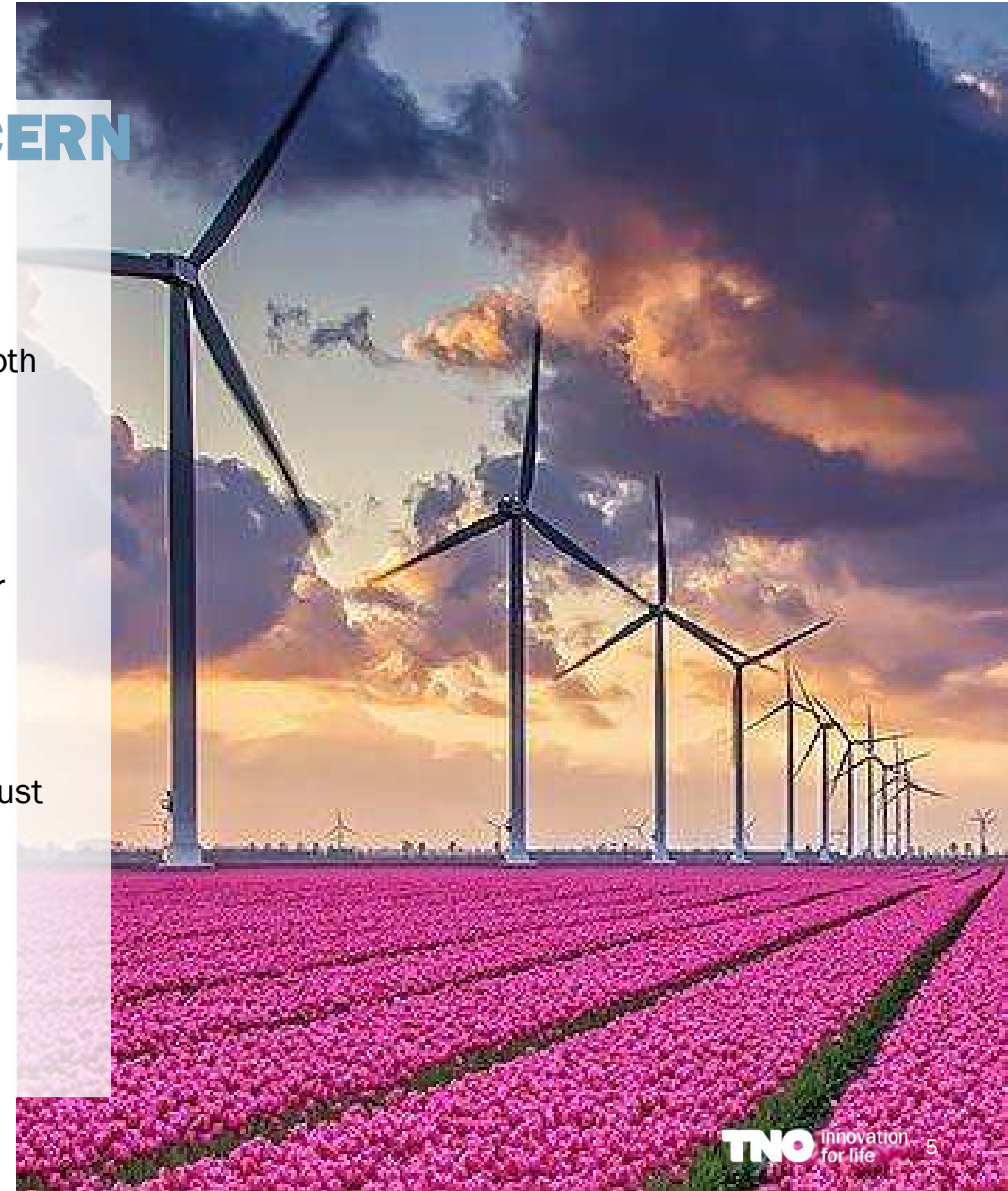
Nine Air Traffic Control radars



High density of wind turbines expected to increase even more !!

## › (CONFLICTING) ISSUES OF CONCERN

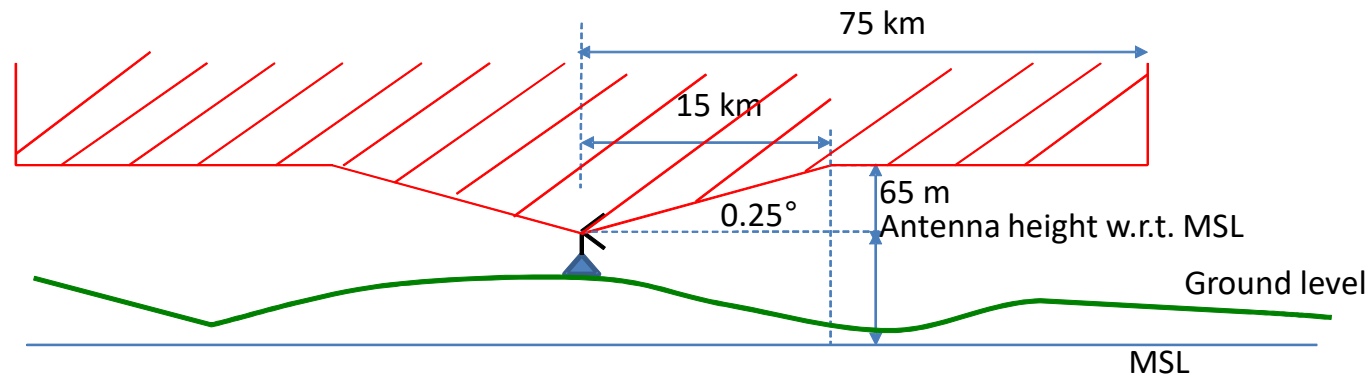
- › Densely populated country, with extensive aerospace activity (both civil and military).
- › All flat country.
- › Small country (approx. 200 x 300 km) in relation to typical radar ranges, hence many issues for only a handful of radars.
- › Ministry of Economics wants to increase the number of wind turbines. The operation of the ATC and military radar systems must be safeguarded.
- › Wind farm – radar interaction still a major issue, but solutions available.



# › REGULATIONS IN THE NETHERLANDS INCLUDING INTRODUCTION TO PERSEUS

## › ASSESSMENT CRITERIA FOR WIND TURBINES

- › Assessment criteria wind turbines restriction area (based on Building Restricted Area (BRA) from ICAO):
  - › The tip of the blade (i.e. maximum height of turbine) must not stick through a cone around a radar position, otherwise it must be assessed by TNO
  - › Cone angle  $0.25^\circ$  starting at primary radar antenna height
  - › Cone diameter 15 km
  - › Between 15 km and 75 km tip of blade not higher than 65 m + primary radar antenna height, referenced to Mean Sea Level (MSL)



# › CIVIL AND MILITARY AIR TRAFFIC CONTROL RADARS THEY ALL PROVIDE A COMBINED RADAR PICTURE

## › Military

- › Leeuwarden
- › Soesterberg
- › Twenthe
- › Volkel
- › Woensdrecht
- › De Kooy
- › Wemeldinge (in-fill)

## › Civil

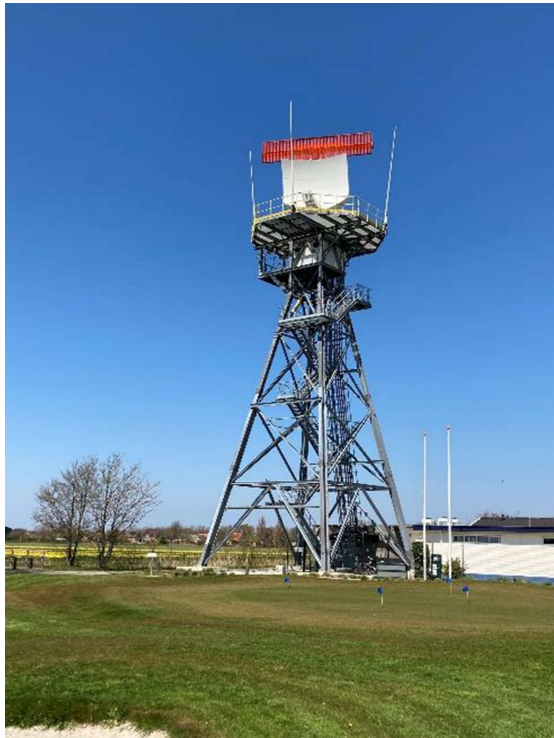
- › TAR West (Schiphol)
- › Belgium military
- › Kleine Brogel



# CIVIL AND MILITARY AIR TRAFFIC CONTROL RADARS

## RECENT EXTENSIONS OF THE RADAR NETWORK

Hensholdt  
ASR-NG De Kooy



Terma Scanter 4002  
Wemeldinge

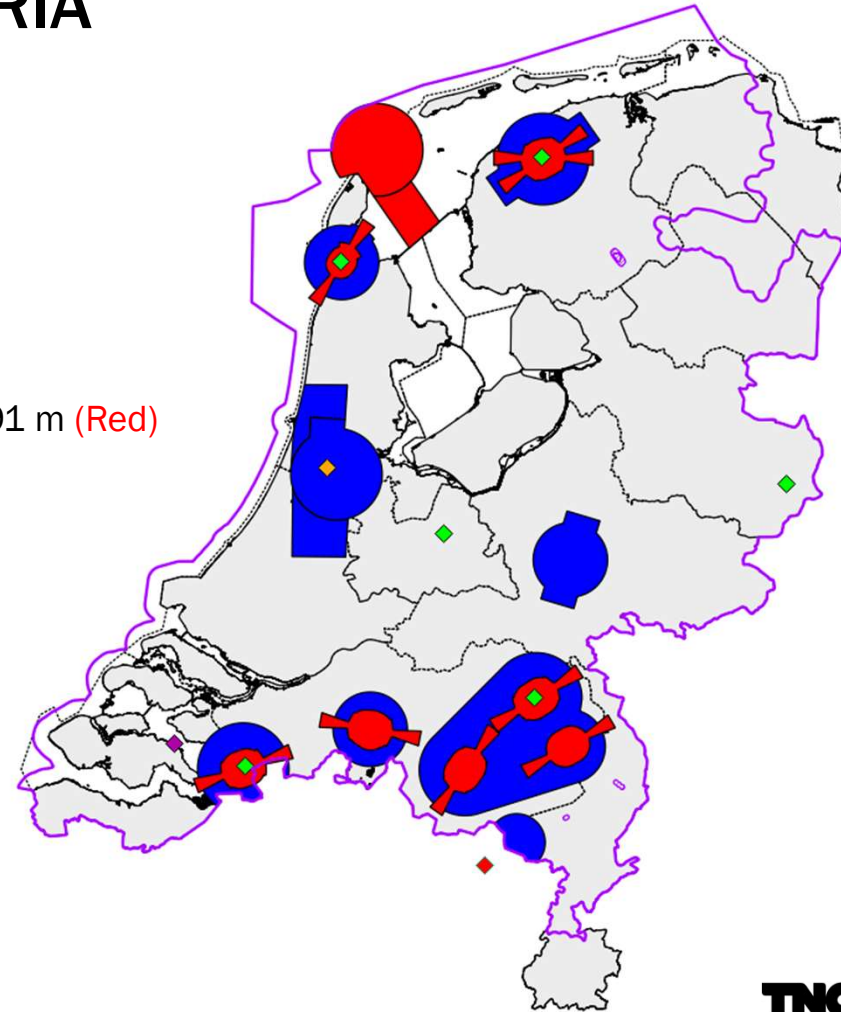


Intersoft-Electronics  
ASR-M Kleine Brogel



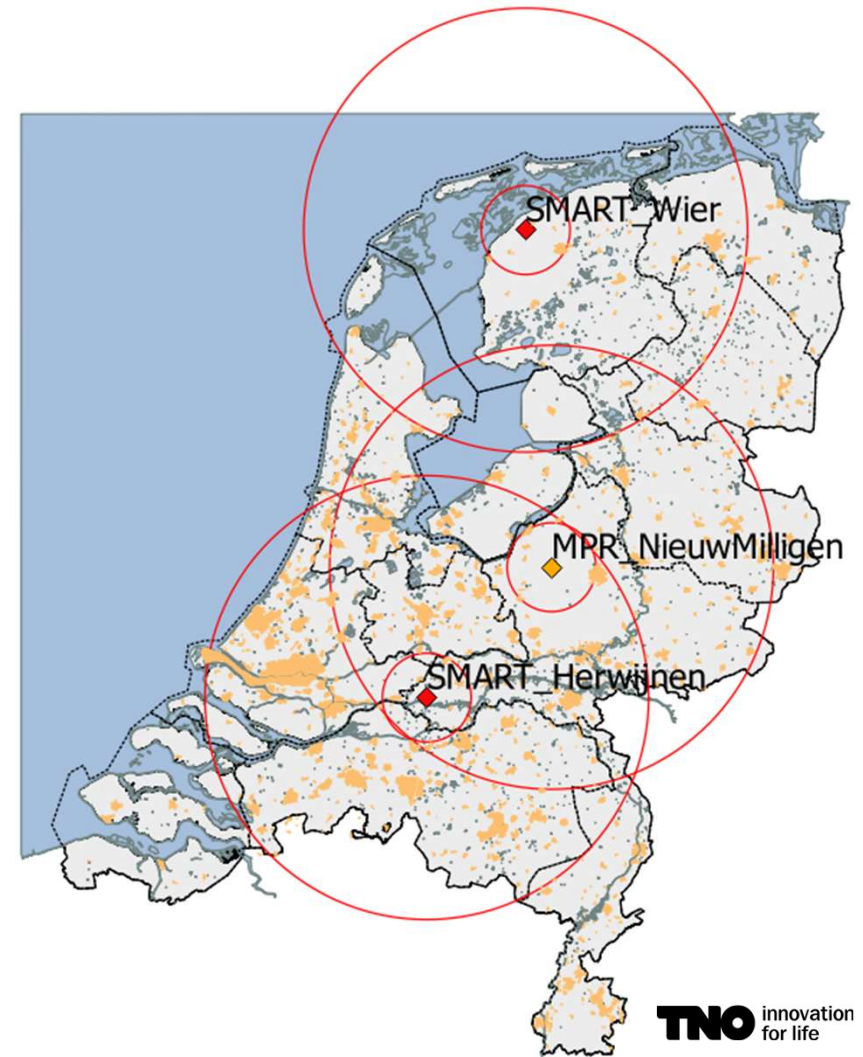
# › CIVIL AND MILITARY AIR TRAFFIC CONTROL RADARS DIFFERENT TARGET HEIGHT CRITERIA

- › Overall coverage: 1000 ft or  $\approx 305$  m (Purple)
- › Controlled traffic region (CTR): 500 ft or  $\approx 152$  m (Blue)
- › Inner Horizontal Conical Sector (IHCS) and funnels: 300 ft or  $\approx 91$  m (Red)
- › Note: Heights are referenced to ground level



# › MILITARY FIGHTER CONTROL RADARS (3D) ARE BEING MODERNISED

- › Thales SMART-L EWC GB
  - › Wier
  - › Herwijnen
- › Nieuw Milligen (MPR)



## › WIND TURBINE MODELLING 3 D CAD DRAWINGS

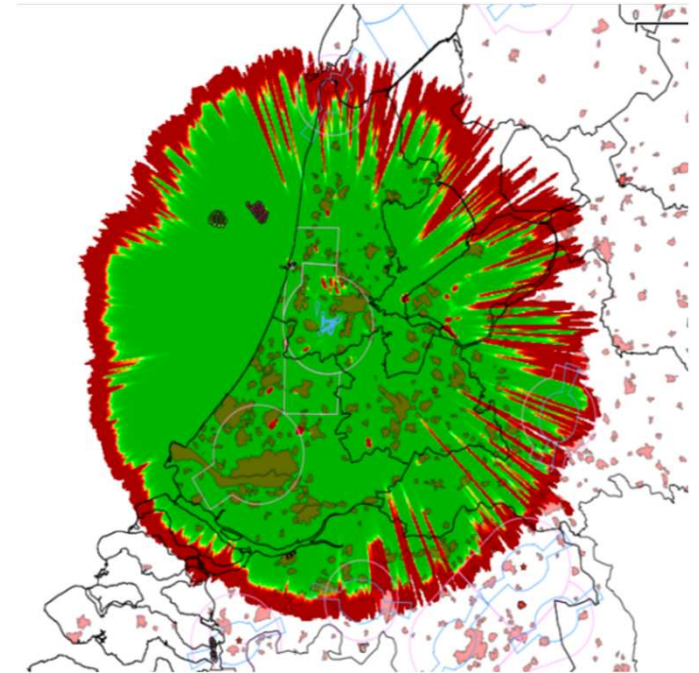
- › Based on 3D CAD drawings provided by all major wind turbines manufacturers:
  - › Enercon
  - › EWT
  - › GE (previously Alstom)
  - › Goldwind
  - › Lagerwey
  - › Nordex
  - › Senvion
  - › Siemens-Gamesa
  - › Vensys
  - › Vestas



## › PERSEUS TOOLKIT

### PROGRAM FOR THE EVALUATION OF RADAR SYSTEMS IN AN EXTENDED URBAN SETTING

- › Compliance with existing guidelines
  - › ICAO EUR DOC 015 (2009)
  - › CAA CAP 764 (2010)
  - › Eurocontrol Guideline (2014)
- › Wind turbine static & moving parts
- › Desensitization Overhead: CFAR processing & pulse compression
- › Shadow Effect
- › Multiple-radar data fusion gap fillers
- › Line-of-sight and diffraction (TERPEM) based on SRTM terrain height database
- › Volumetric assessment
- › Versatile radar modelling (based on TNO's CARPET, with 700+ licenses sold worldwide)

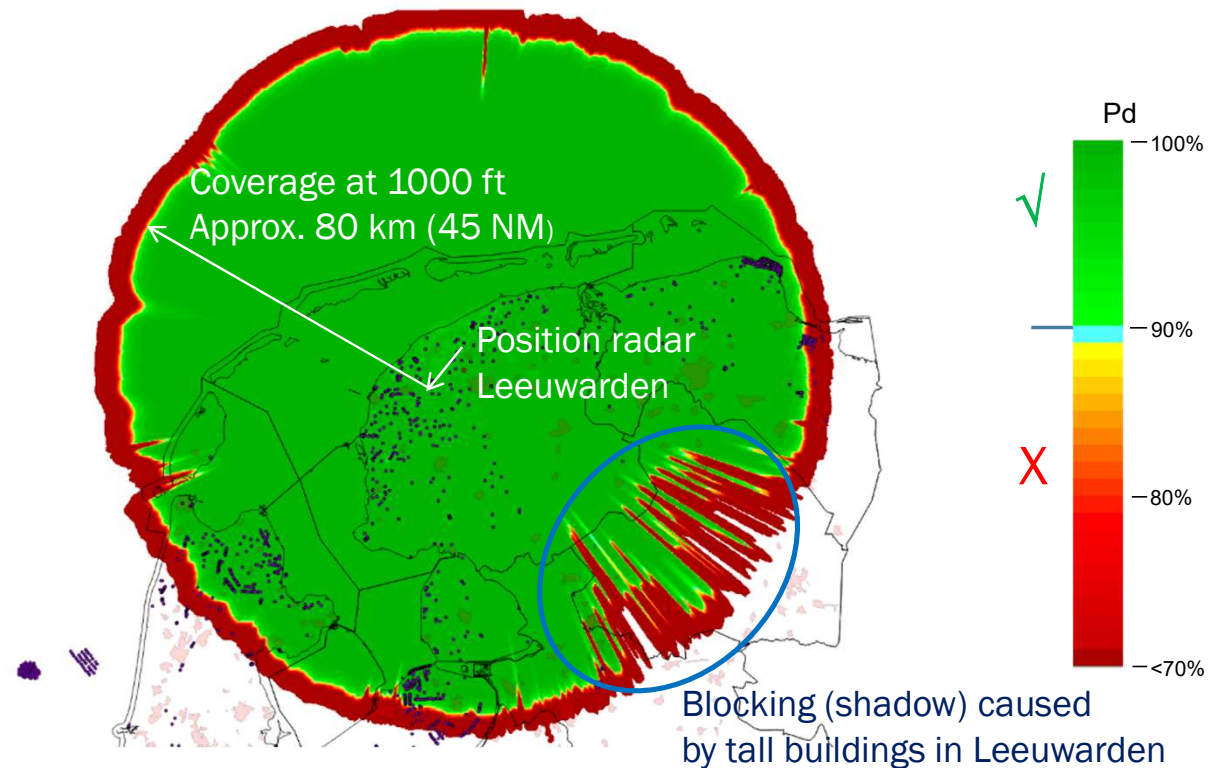


# PERSEUS TOOLKIT

## RADAR PERFORMANCE CALCULATIONS

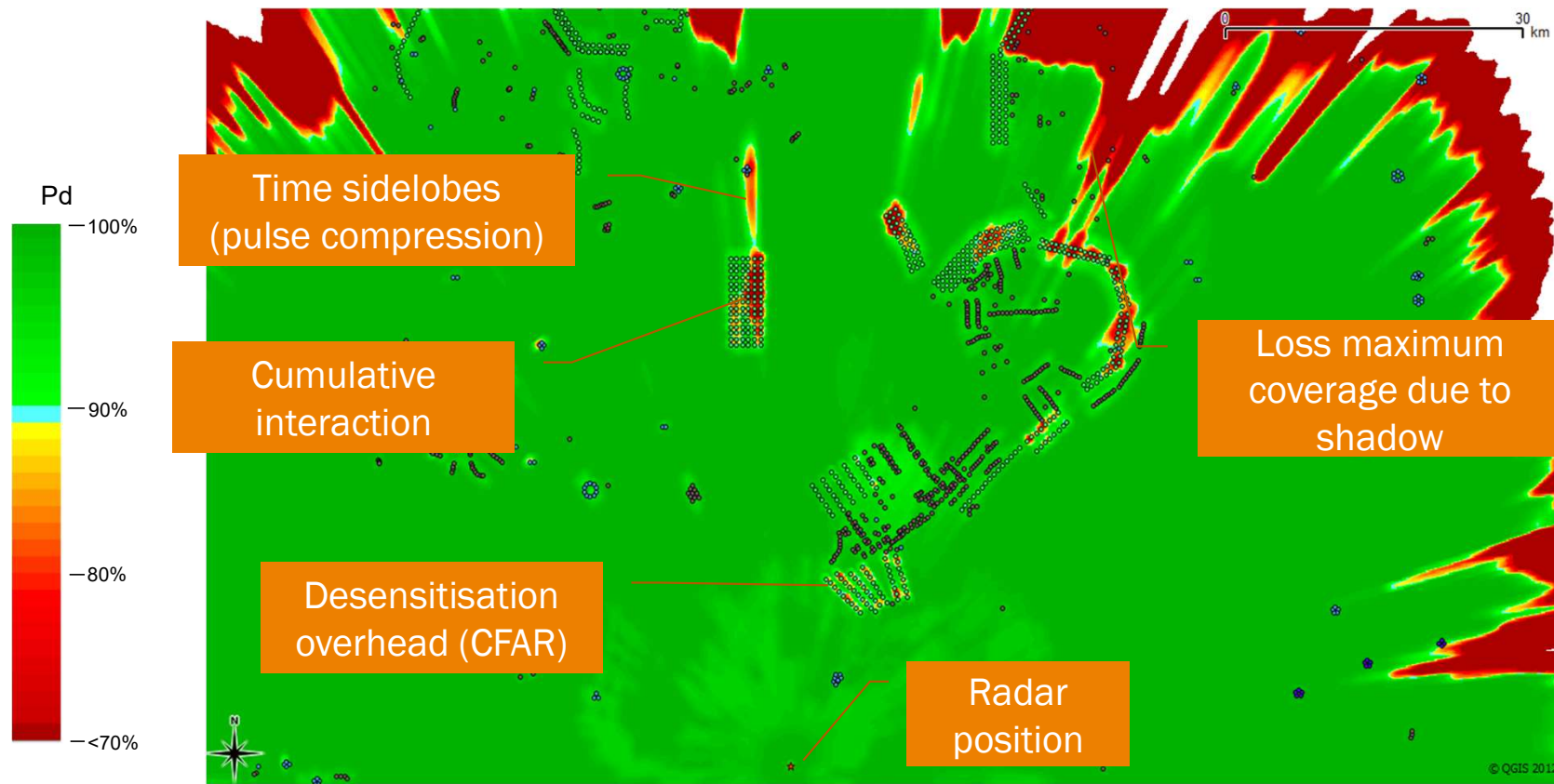
- › Single scan detection probability ( $P_d$ ) of a target (aircraft) having a radar cross section (RCS) of 2 m<sup>2</sup> at a target height of 300, 500 and 1000 ft.
- › Data from all air traffic control radar are fused to a single picture.
- › Criteria 1 densitisation overhead:
  - › Minimum detection probability shall be  $\geq$  90%.
- › Criteria 2 shadow effect:
  - › The loss of detection range at 1000 ft shall be  $\leq$  2 km

Example: MASS radar Leeuwarden,  
Target height 1000 ft



## PERSEUS TOOLKIT

# COVERAGE DIAGRAM (1000 FT) INCLUDING WIND TURBINE INTERFERENCE EFFECTS

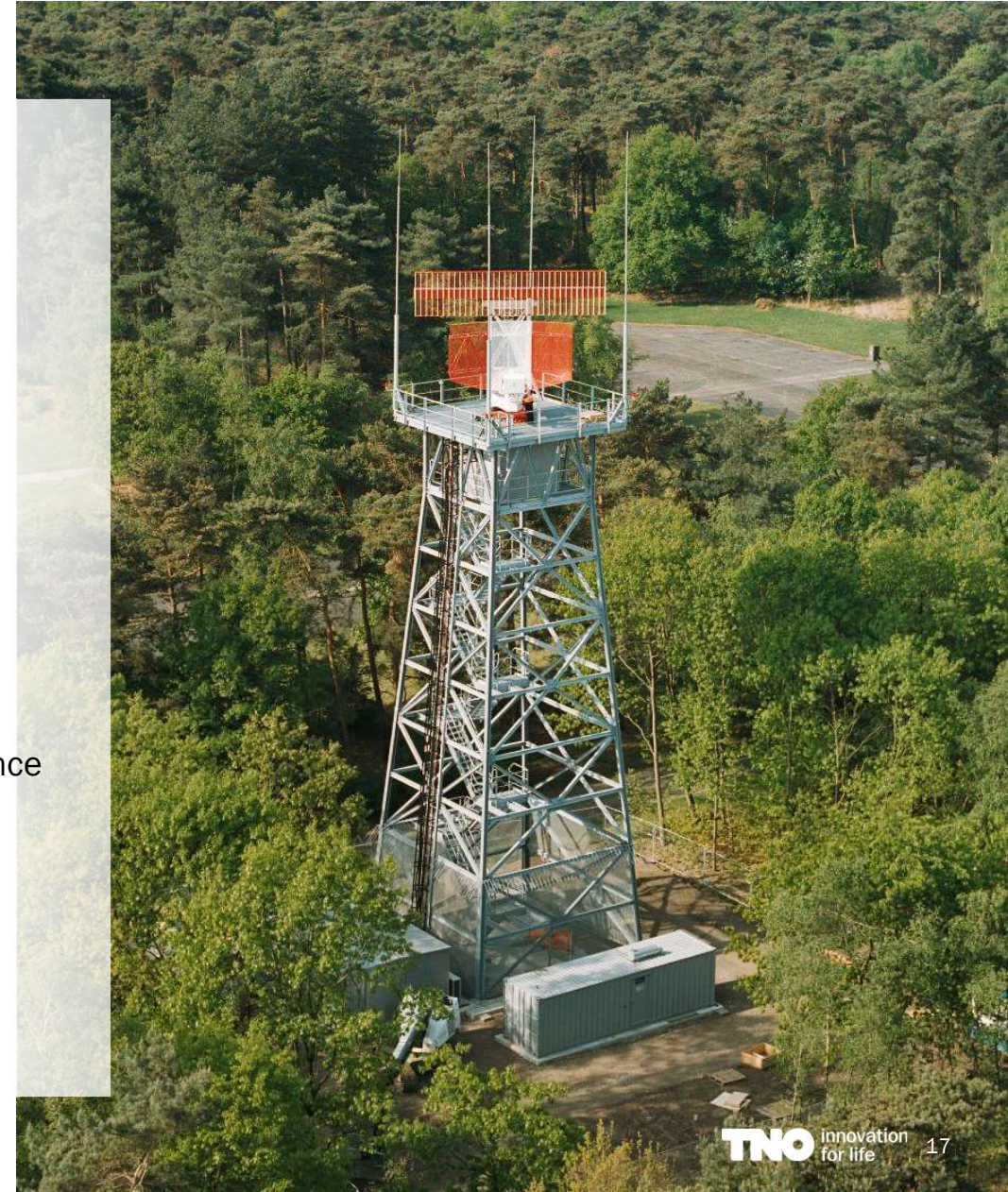


# › MITIGATION MEASURES

## SOME EXAMPLES

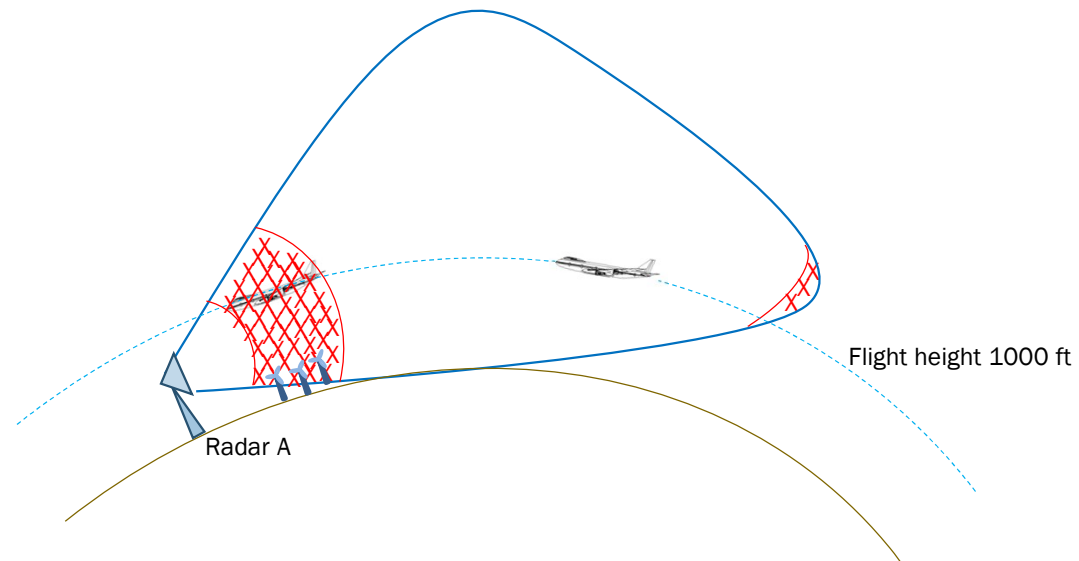
## › MITIGATION MEASURES SOME EXAMPLES

- › Wind turbine adaptations:
  - › Smaller design
  - › Radar orientation avoidance (only effective for a single radar situation)
  - › Radar absorbing (blade) materials or coatings (limited effect)
- › Radar system adaptations:
  - › Radar fusion of data from multiple radars, e.g. **ATM suRveillance Tracker And Server (ARTAS)** of EUROCONTROL, combined with additional radars
  - › Realisation of additional radars including in-fill radars
  - › 3D radars instead of 2D radars
  - › Processing improvements within the radar



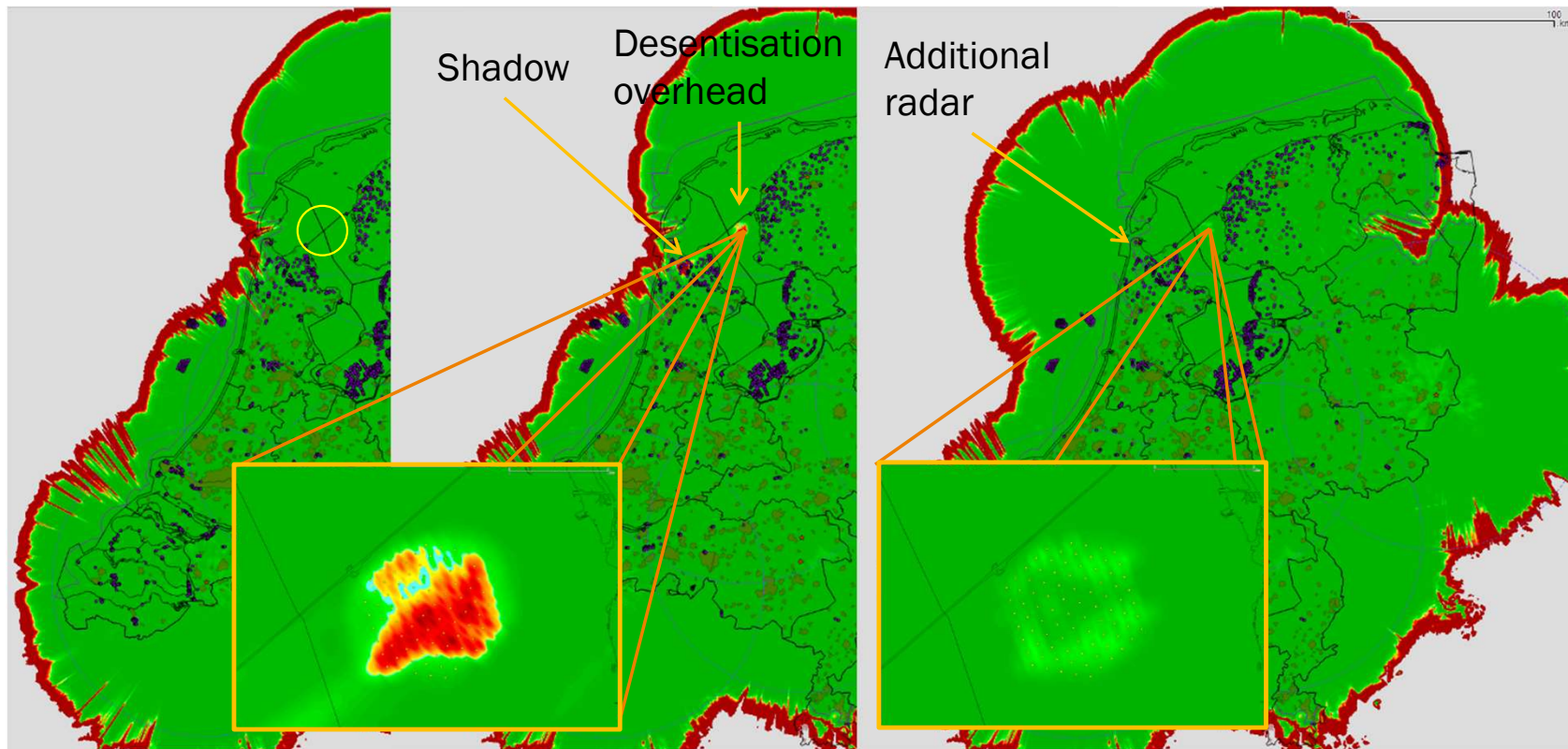
# › MITIGATION MEASURES

## DATA FUSION OF MULTIPLE RADARS





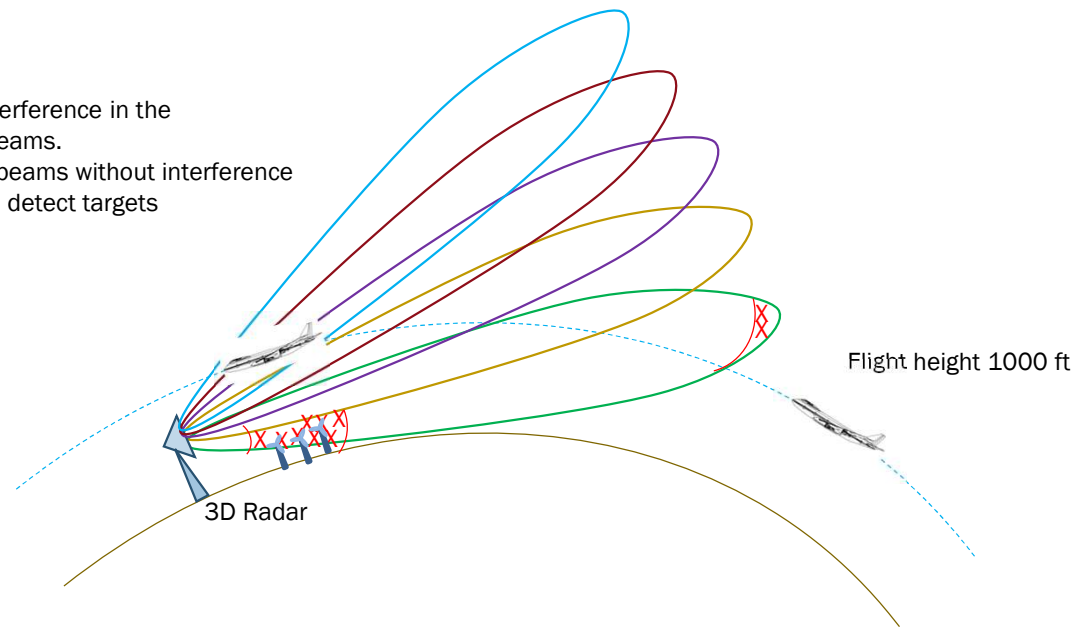
# MITIGATION MEASURES ACTUALLY IMPLEMENTED IN THE NETHERLANDS



# › MITIGATION MEASURES

## 3D RADAR OPERATION

Only interference in the lower beams.  
Higher beams without interference  
can still detect targets

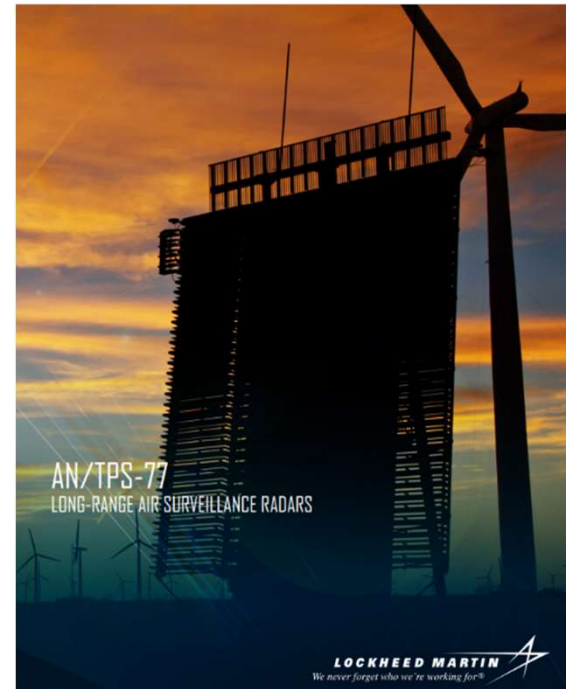


## › MITIGATION MEASURES ACTUALLY IMPLEMENTED

Thales SMART-L Fighter  
Control radar in The Netherlands



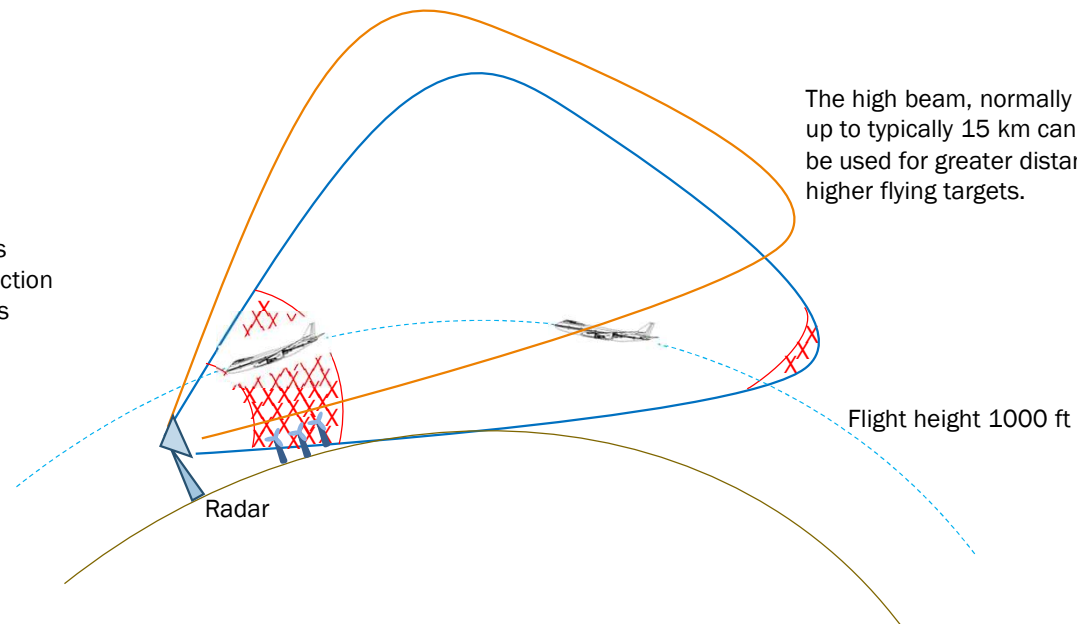
Lockheed-Martin AN/TPS-77  
Air surveillance near the coast  
of the United Kingdom



# › MITIGATION MEASURES

## PARALLEL PROCESSING LOW AND HIGH BEAM

High beam provides non-interfered detection above wind turbines



The high beam, normally only used up to typically 15 km can now be used for greater distances for higher flying targets.

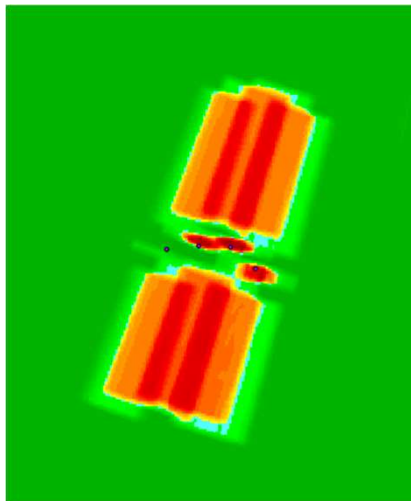
Flight height 1000 ft

# › MITIGATION MEASURES (CFAR) PROCESSING ENHANCEMENTS

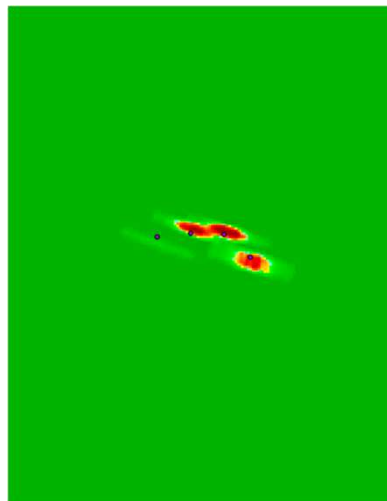
› Actual examples:

- › Raytheon ASR-10SS
- › Thales STAR 2000 (WFF)

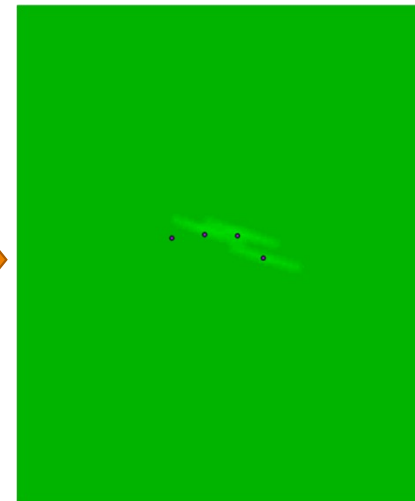
Standard (CAGO) operation  
Target at 1000 ft



Enhanced operation  
Target at 1000 ft



Parallel processing  
high-low beams  
Target at 4000 ft



## › MITIGATION MEASURES

# IN-FILL RADAR MARKET SURVEY PERFORMED FOR GOVERNMENT

Holographic radar, Aveillant (UK)



LSTAR radar, SRC (US)



Light Wave radar, C-Speed (US)



Scanter 4002, Terma (DK)



## › MITIGATION MEASURES

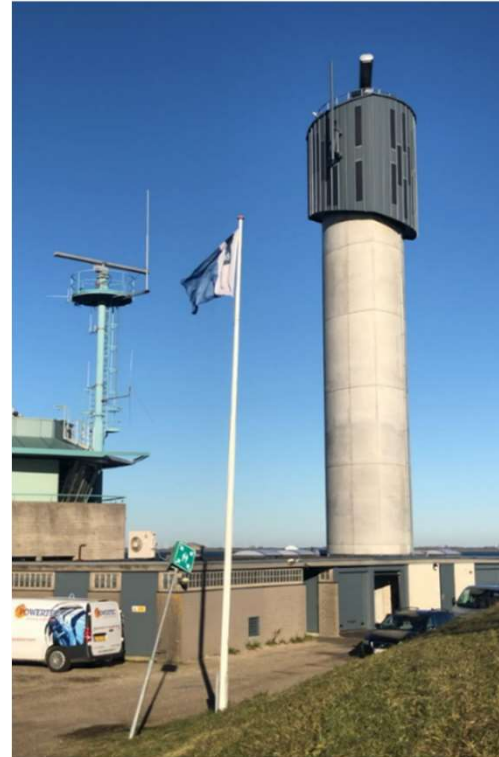
# SCANTER 4002 IN-FILL RADAR ACTUALLY IMPLEMENTED

Multiple SCANTER radars installed at UK airports by NATS. For instance at Newcastle Airport (UK).



<https://neconnected.co.uk/state-art-radar-surveillance-system-comes-newcastle-airport/>

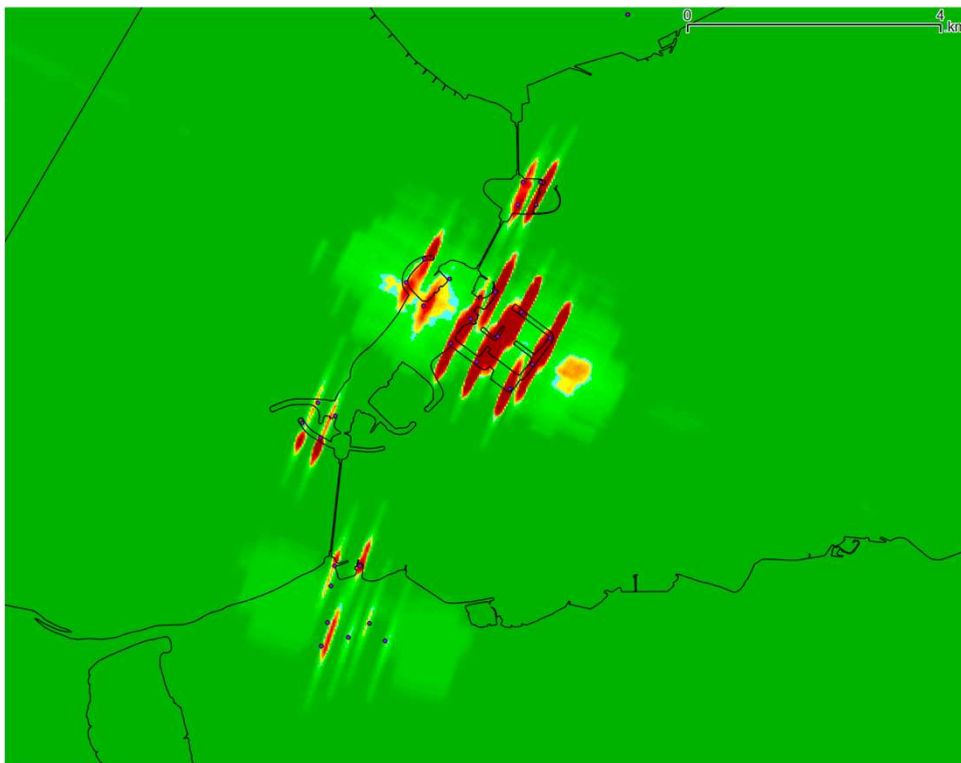
SCANTER 4002 installation at Wemeldinge Zeeland (NL)



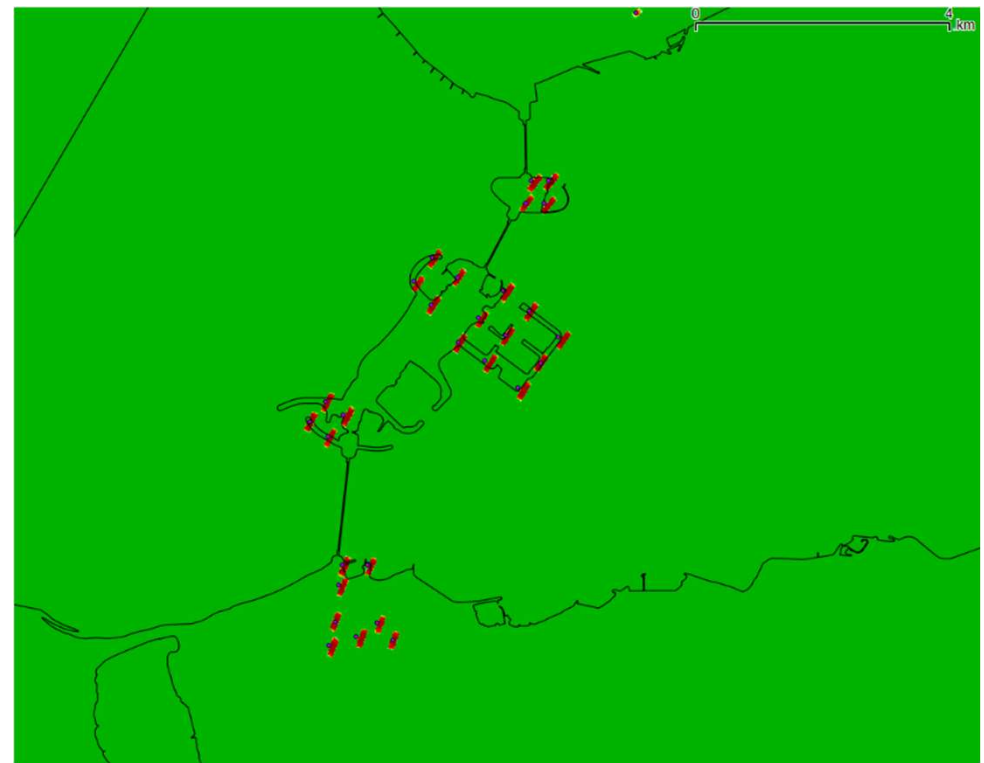
## MITIGATION MEASURES

### SCANTER 4002 IN-FILL RADAR (SIMULATED RESULTS)

Conventional ATC radar (MASS Woensdrecht)



SCANTER 4002 infill radar (Wemeldinge)



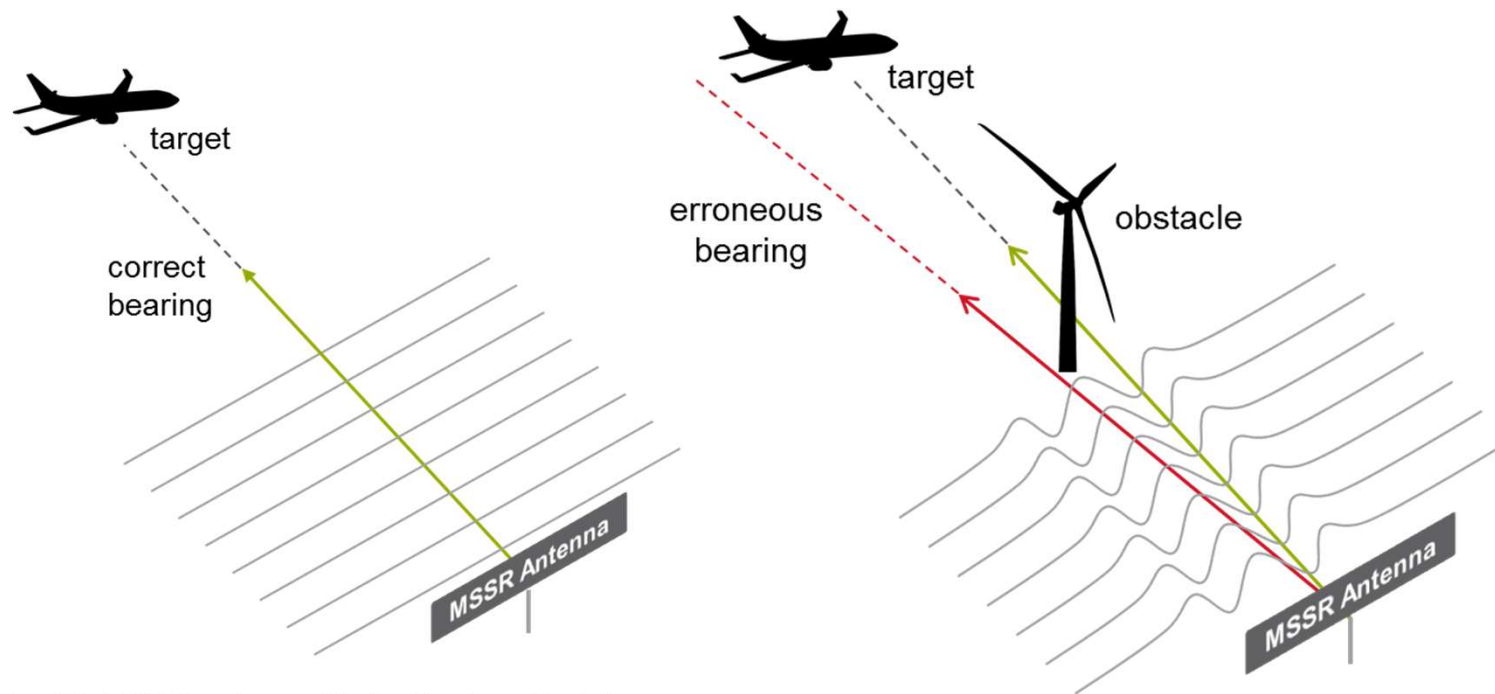
# › SECONDARY RADAR

## WIND TURBINE INTERFERENCE



## › SECONDARY RADAR OFF-BORESIGHT ERRORS (OBE)

- › Wind turbines, positioned between target and MSSR antenna can disturb the transponder signal, introducing an error in the bearing estimate
- › Included in PERSEUS toolkit

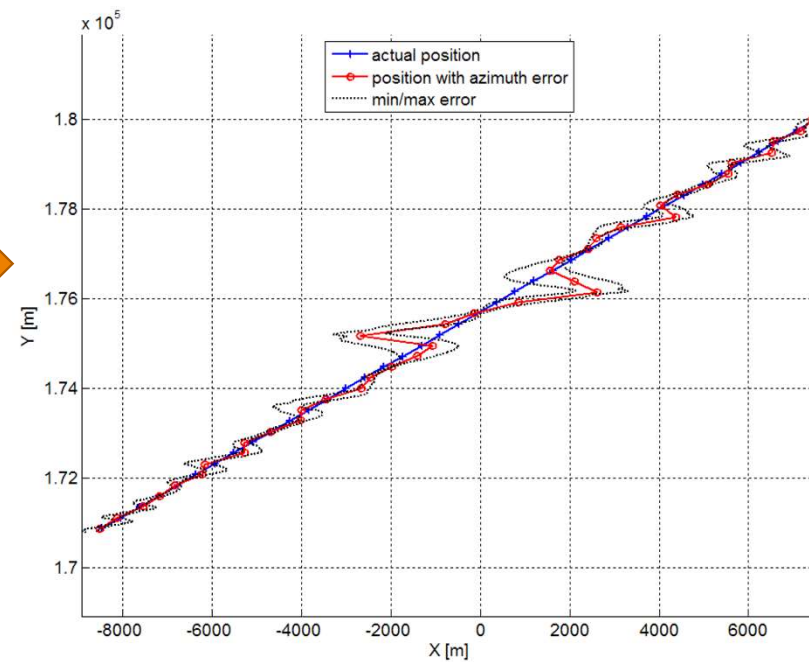


# › SECONDARY RADAR VALIDATION OF SIMULATED RESULTS

› Effects on the MSSR of the Control Tower at Zaventem



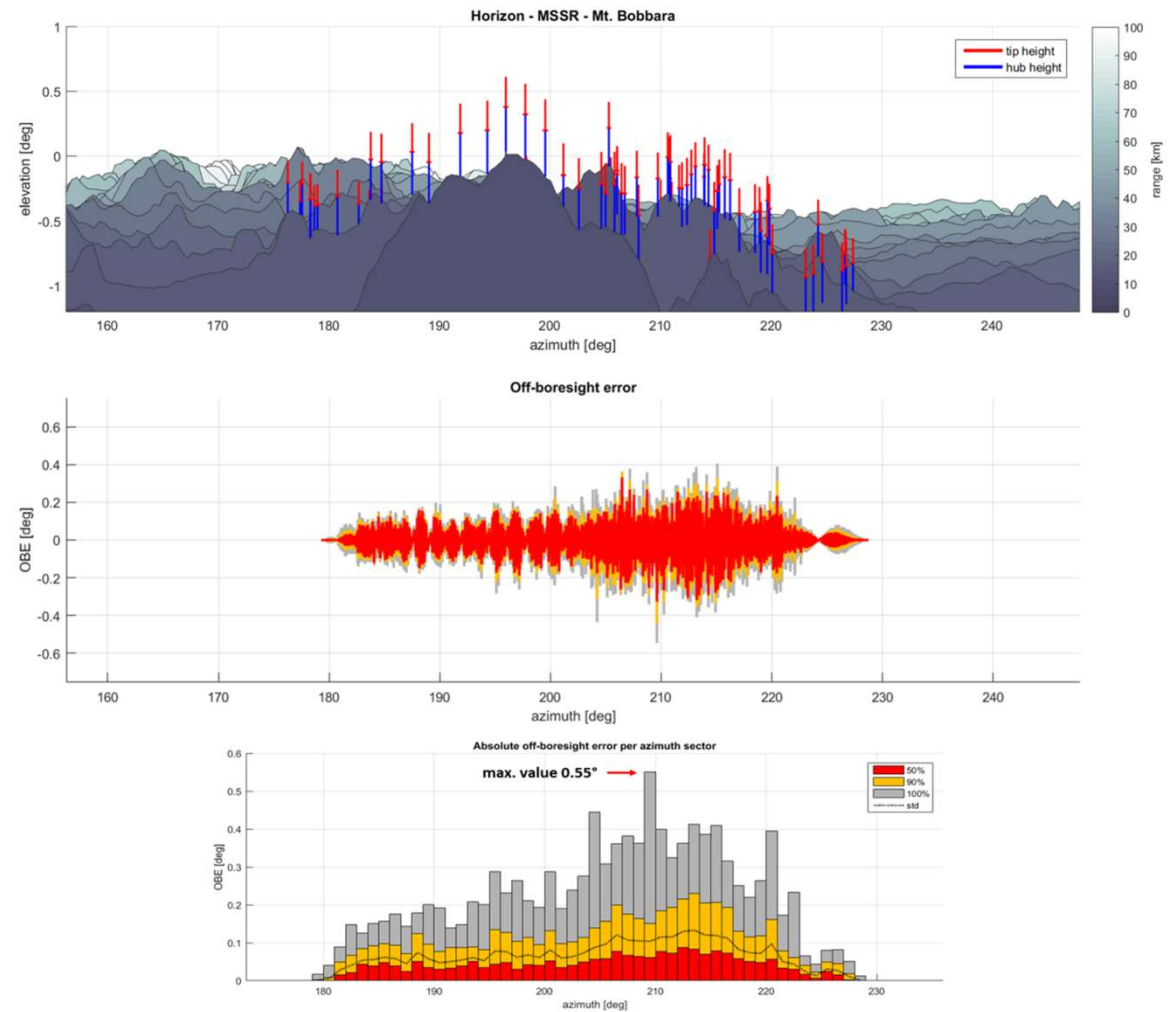
Recorded Real track



Simulated track

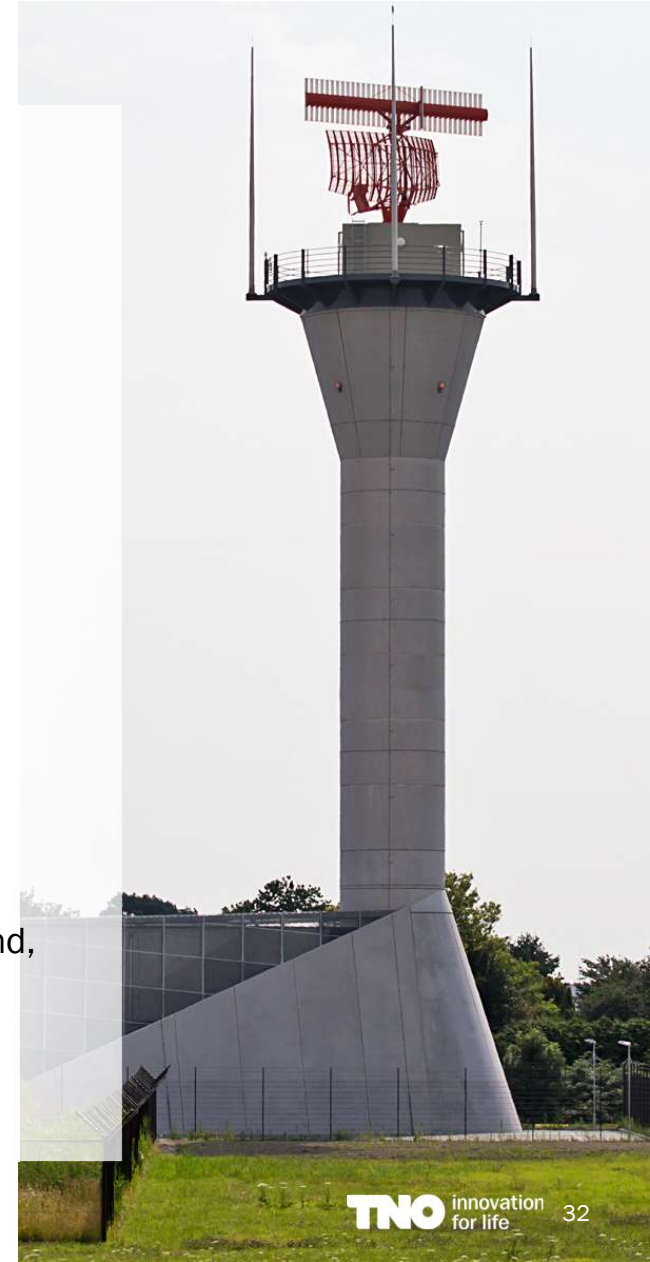
# SECONDARY RADAR MULTIPLE WIND TURBINES

- › Line-of-sight analysis
- › Digital elevation model (DEM)
- › Off Boresight Error (OBE) calculation
- › Absolute OBE per azimuth sector



## › NLD EXPERIENCE IMPACT TO ATC RADARS SUMMARY

- › Wind turbines cause interference on radars.
- › The Netherlands developed a successful assessment and mitigation scheme
- › **PERSEUS toolkit has a central role**
- › With conflicting interest between government & industry TNO is often involved as a independent intermediate.
- › Involved in international studies in Belgium, Denmark, Finland, Sweden, France, Switzerland, United Kingdom and Australia





› **THANK YOU FOR  
YOUR TIME**

**TNO** innovation  
for life