Appendix 3

Moorshield Wind Farm

Independent Assessment of Feasibility for Moorshield Wind Turbines by Helios

Moorshield Wind Farm Limited

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Independent assessment of feasibility for Moorshield wind turbines mitigation

Report for Moorshield Wind Farm Limited

an egis company

Document information

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Version	Date	Author	Description of the changes
1.0	14/02/2020	Adam Parkinson	Initial release of document containing Moorshield analysis based on original wind turbine mitigation feasibility analysis conducted for proposed Soame wind farm.
1.1	04/06/2020	Adam Parkinson	Correction to GPA antenna height, and location of wind turbine 3 in annex A. Update of line of sight analysis figures and text taking into account new GPA antenna height (Table 1, § 3.2.1, Figure 12, § 3.2.2, Figure 17, § 3.2.3, Figure 23, § 4)

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1 Introduction

1.1 Document purpose

This document has been prepared by Helios for Moorshield Wind Farm Limited in the planned development of the Moorshield wind farm.

The purpose of this report is to provide an initial, independent assessment of the feasibility of identifying a technical solution to mitigate the potential effects that the Moorshield wind farm will have on the NATS En-route (NERL) primary radar at Lowther Hill.

1.2 Disclaimer

The report provides our initial expert opinion based on the information available and our knowledge of civil Air Traffic Control surveillance systems and wind farm mitigation solutions. It cannot be taken as conclusive evidence on its own on the technical, operational, financial and contractual viability of any specific mitigation solution for Moorshield. In particular, any potential mitigation solution needs to be assessed by NERL and, where a mitigation solution is based on an existing system, the installers and operators of the that system.

1.3 Background

Moorshield Wind Farm Limited is working on a plan to develop the Moorshield wind farm, which is located on the north side of the existing Whitelee wind farm (see Figure 7). The previous Soame application was refused planning permission by East Renfrewshire Council, partly because of objections to its impact on the normal operation of the NERL Air Traffic Control (ATC) primary radar at Lowther Hill which monitors en-route traffic, and the ATC radar at Glasgow Airport. The Lowther Hill radar is used to support the provision of safety critical, surveillance based en-route Air Traffic Services (ATS) from the NATS Air Traffic Control Centre (ATCC) at Prestwick.

Based on this previous application and subsequent appeal by Moorhouse Wind Farm Ltd in relation to the Soame wind turbine development, it was recognised by Glasgow Airport, NATS, and East Renfrewshire Council that the Kincardine infill radar and the secondary option of a Terma Scanter 4002 provided suitable mitigation for the proposed wind turbines[1]. It is therefore likely these mitigation options will still be applicable to the proposed Moorshield turbines as a result of their proximity to the original Soame site. This is investigated further within the document.

Glasgow Airport has installed a new Terma Scanter 4002 radar which offers improved performance in the presence of wind turbines. Now the radar is operational, it is expected that any objection to the Moorshield wind farm by Glasgow Airport will be removed.

In order to overcome an objection from NERL a radar mitigation solution needs to be agreed to mitigate the impact of proposed Moorshield wind turbines on the Lowther Hill ATC primary radar. One mitigation solution for Lowther Hill is to take a feed from the Kincardine radar to replace the Lowther Hill data in the affected area, which was the original mitigation solution for Whitelee and the reason why the Kincardine radar was installed. Moorshield Wind Farm Ltd is also considering possible alternate mitigation solutions including using a feed from the new Terma radar at Glasgow Airport.

[1] Available at: https://www.dpea.scotland.gov.uk/CaseDetails.aspx?ID=118722

1.4 Who are Helios?

Helios is a leading independent consultancy specialising in air transport, airports and air traffic management. We work with a wide range of organisations – airports, airlines, air navigation service providers, regulators, government agencies, manufacturing industry, development agencies and investors - to be at the forefront of the industry's latest developments: such as the Single European Sky initiative, Functional Airspace Blocks, private sector participation in airports and air traffic management, and the move towards a performance-based aviation system. We understand all aspects of the air transport business ranging from the strategic, through the operational and technical, to R&D.

Helios provides comprehensive consultancy support across all aspects of the Air Traffic Management (ATM) industry and through the ATM system development, procurement and implementation lifecycle. We also have contacts and good relationships with all the key stakeholder groups concerned with the impact of wind farms on ATM, although we are independent from them. This includes NATS, CAA, wind farm developers, radar manufacturers, airport operators and ATS providers.

Helios has provided advice to a number of different organisations in relation to the impact of wind farms on radars, and mitigation solutions. This includes:

- providing technical support to the Eurocontrol Wind Turbine Task Force
- providing independent advice on the technical mitigation proposed for the Clyde wind farm
- conducting independent performance analysis of different technical mitigation solutions in the presence of wind farms
- providing due diligence advice to banks funding the procurement of Terma Scanter 4002 radar as wind farm mitigation solutions.

1.5 Simplified description of the impact of wind turbines on ATC radars

There are two main types of ATC surveillance radar:

- A **Primary Surveillance Radar (PSR)** works by sending out a radio frequency electromagnetic pulse that is reflected by the aircraft and received back at the radar. The range and bearing of the aircraft is calculated based on the direction the radar antenna was pointing and round-trip time for the pulse.
  - Strengths: requires no specific equipment so works with many different types of aeronautical systems.
  - Weaknesses: provides no altitude or identity information on aircraft; susceptible to interference resulting in loss of detection of aircraft or presentation of 'false targets' to Air Traffic Controllers (a false target is a plot displayed on a radar screen that does not represent a real aircraft in that location); only provides slant range (the distance through the air to the aircraft – not the distance along the ground).
- A **Secondary Surveillance Radar (SSR)** works in a similar way to a primary radar except that the radar sends out a small data packet and the aircraft is equipped with a compatible transponder to decode and reply to the data packet. The reply from the aircraft transponder includes additional information on the aircraft such as altitude and identity.

- Strength: greater range of information on aircraft compared to primary radar; higher accuracy and probability of detection; greater resistance to interference.
- Weaknesses: requires aircraft to carry specific equipment.

Wind turbines cause interference to ATC radars as they reflect the radio frequency electromagnetic pulses that are then received by the radar. While both primary and secondary radars can be affected by wind turbines they have a greater impact on primary radars which are inherently more susceptible to interference. Although existing primary radars are typically designed with filters to reduce the impact of interference on the information displayed to an Air Traffic Controller they are not effective against wind turbines. In particular, the speed of the wind turbine blades is similar to the speed of an aircraft and therefore a wind turbine looks just like an aircraft to a primary radar.

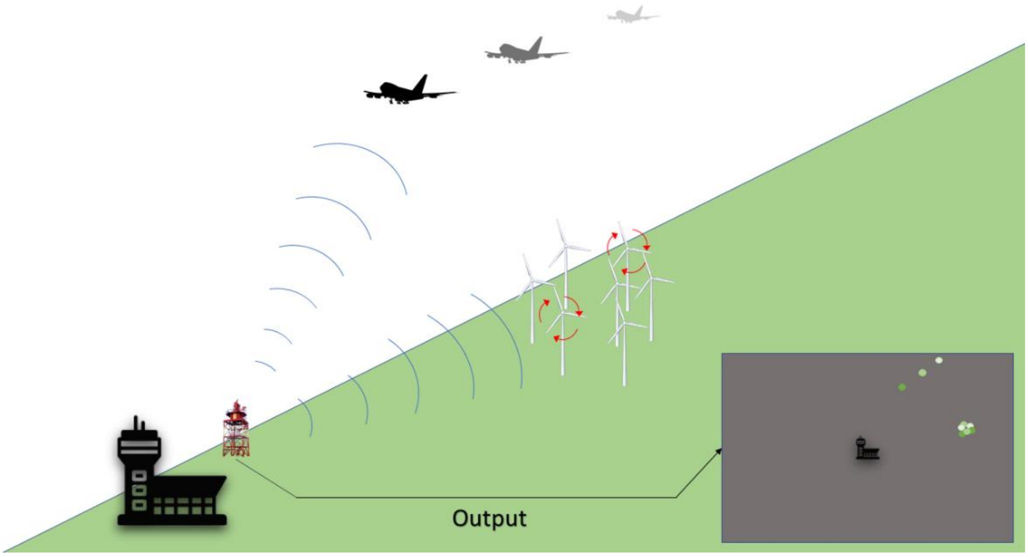

Figure 1: Illustration of the interference of wind turbines on ATC PSR radar display

The remainder of this report only focusses on primary radar mitigation.

1.6 Mitigating the effects of wind turbines on ATC primary radars

The Moorshield wind farm will potentially cause interference (e.g. loss of detection of real aircraft, or the presentation of false targets) on the Air Traffic Control displays in the NERL Prestwick ATCC. Any mitigation solution needs to provide ‘clean’ primary surveillance (i.e. radar) data to Prestwick ATCC in the airspace over the Moorshield wind farm to meet the Air Traffic Control operational requirements.

While there are potentially different approaches to mitigation, each with different strengths and weaknesses, this initial feasibility assessment has focussed on an ‘in-fill’ mitigation solution. In this approach a second primary radar, unaffected by the specific wind turbines under consideration, is used to provide radar data in the area over the wind turbines (the in-fill area) in place of data from the affected radar. This approach has been successfully tried and tested as a mitigation solution for other wind turbines and is likely to be the most feasible solution to implement in the short term.

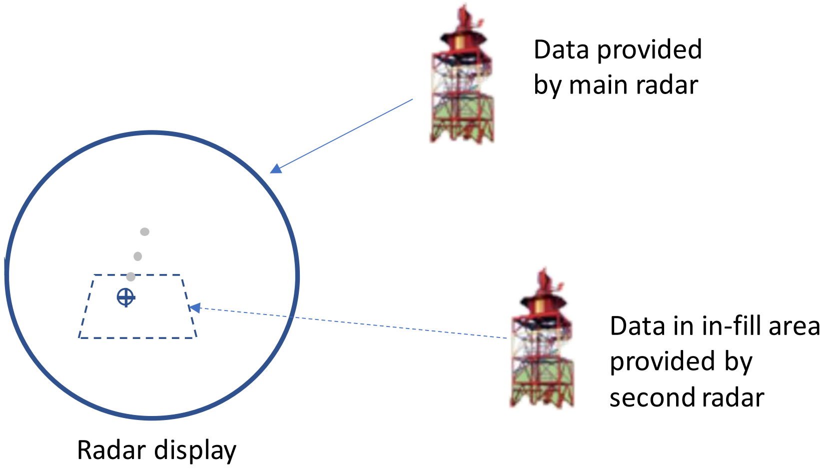

Figure 2: Illustration of an 'in-fill' mosaic radar display

For a primary radar to be feasible as an in-fill solution it needs to provide the required coverage (minimum and maximum altitude) in the volume of airspace over the wind turbines. It also either needs to be resistant to the interference caused by wind turbines, or the wind turbine needs to be out of Line of Sight (LoS) of the radar. A final consideration is the slant range errors associated with the in-fill radar i.e. the different between the actual position of the aircraft over the ground and the position displayed on a controller's radar screen.

1.7 Scope

The primary objective of this initial feasibility assessment is to identify whether there are any existing primary radars that can provide 'clean' primary radar data in the airspace over the Moorshield wind farm to meet the Air Traffic Control operational requirements. A particular focus has been requested to consider the use of the new Terma Scanter 4002 radar at Glasgow Airport, but other radar options are also considered.

The scope of our assessment of the feasibility of radar mitigation options for Moorshield (in respect of the NERL Lowther Hill radar) therefore consists of the following steps:

- identification of existing civil ATC radars that could provide 'in-fill' data over the Moorshield wind farm for use in the Prestwick ATCC in place of the data from the Lowther Hill radar
- assessment of the coverage volume of the identified radars in the airspace over the Moorshield wind farm also considering the airspace structure around the wind farm
- estimate of the slant range errors of the identified radars and whether they would meet NATS requirements to be able to use the data in the Prestwick ATCC to support en-route three nautical mile surveillance separation service
- assessment of the likely probability of detection performance of the Terma radar in the airspace over the Moorshield wind farm based on previous trials of the Terma radar
- review of other known planned implementations of the Terma Scanter 4002
- initial conclusion on the feasibility of a radar mitigation for Moorshield based on the assessment above.

For the avoidance of doubt the following are explicitly outside the scope of this assessment:

- the procurement of a new radar, or the replacement of any existing radar
- a prediction on the actual performance of a specific radar in the airspace over the Moorshield wind farm.

2 Methods and data used in assessment

2.1 Identification of potential in-fill radar candidates

The following civil ATC primary radars were identified as being close enough to the planned Moorshield wind farm to provide radar coverage over the wind farm and are therefore candidate in-fill radars:

- Cumbernauld
- Glasgow Airport – a Terma Scanter 4002 is installed and operational since early 2019
- Glasgow Prestwick Airport (GPA) – a Terma Scanter 4002 is installed and operational
- Kincardine

2.2 Primary radars

Table 1 lists the data relating to the PSR sites used in this assessment. All coordinates use the WGS84 datum.

PSR Site	Coordinates (Degrees Minutes Seconds)	Antenna height (metres AGL)	Instrumented range (Nautical Miles)	Terrain Elevation at radar site (metres MSL)
Cumbernauld	55°56'21.37"N 4° 3'26.91"W	26.6	60	76
Glasgow Airport Terma[2]	55°52'28.99"N 4°26'8.00"W	17	40	5
GPA Terma	55°30'8.24"N 4°35'1.90"W	22.33	40	18
Kincardine	56° 4'19.99"N 3°43'45.00"W	33.5	80	4
Lowther Hill	55°22'40.15"N 3°45'10.59"W	15	120	720

Table 1: Parameters relating to the radar sites that were used in the analysis

2.3 Moorshield wind farm

The centre of the proposed Moorshield wind farm is expected to be located roughly at 55°42'57"N, 4°21'28"W and consists of 3 wind turbines. The exact coordinates of each of these have been listed in Appendix A. The maximum height of the tip of the wind turbine blades Above Ground Level (AGL) is expected to be 149.9 metres. The hub of each of the wind turbines is expected to reach 81.9 metres AGL.

[2] This information is based on the location and height of the existing radar at Glasgow airport as we do not have the specific details of the new Terma Scanter 4002 installed. However, the location details are assumed to be sufficiently accurate for the purposes of a first order line of sight coverage analysis. The instrumented range is based on that of the Terma Scanter 4002.

2.4 Estimation of radar coverage and wind farm visibility

The Radio Mobile software application was used to assess the Line of Sight (LoS) visibility of the wind farm from the radars and the likely radar coverage. SRTM 1-arc second terrain data was used in all radar LoS and coverage calculations. The visual LoS calculations did not account for obstacles such as buildings or vegetation although these were considered in the point-to-point propagation.

The coverage of a radar is also affected by the antenna gain pattern. In particular the cut-off of the antenna pattern at high elevations results in what is known as a cone-of-silence in the airspace directly over the radar.

A typical ATC PSR antenna gain pattern is shown in Figure 3.

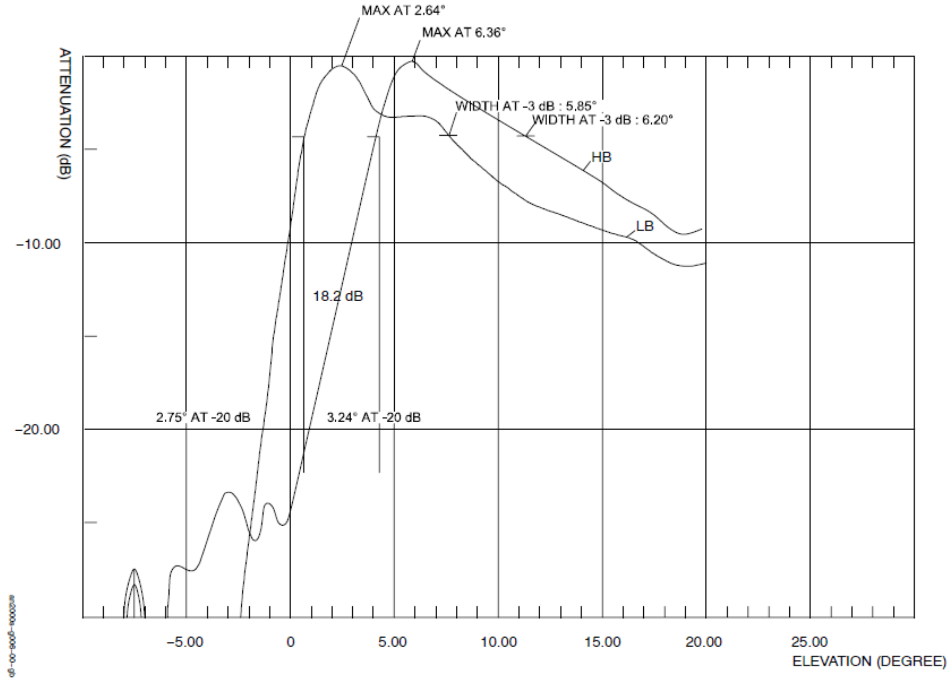

Figure 3: Antenna gain of a typical primary surveillance radar antenna

Note that for the depicted radar the highest sensitivity is at an angle of approximately 2.5 degrees above the horizon for the surveillance antenna.

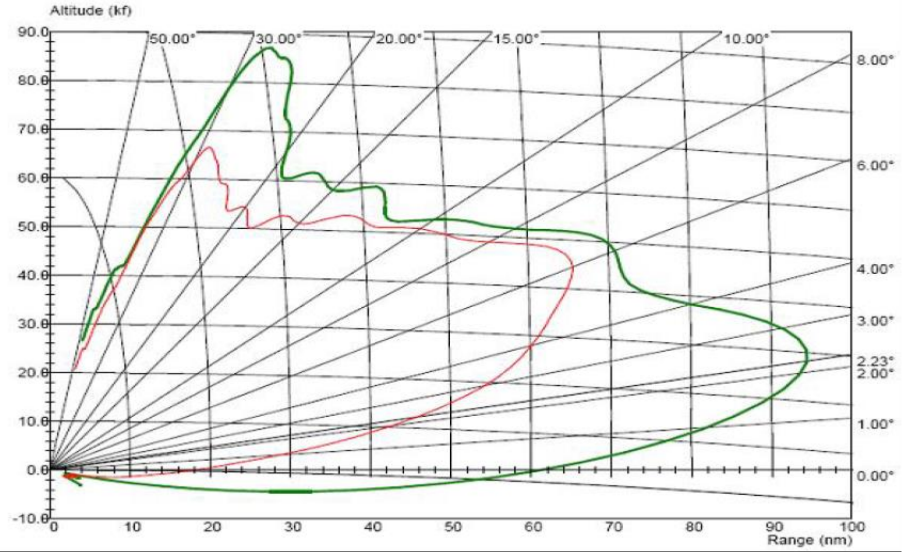

Figure 4: Vertical cross-section of a typical S-band radar coverage due to antenna gain pattern

2.5 Analysis of radar accuracy requirements.

The operational requirement for radar coverage in the airspace above the proposed wind farm was determined from the UK AIP[3]. Based on this an assumption was made on the likely radar accuracy requirements using the data pertaining to radar range and performance found in the Scottish TMA Primary Radar Capability Study conducted by NATS[4]. Finally, data on radar operational capabilities published by Terma Scanter and Indra was used in the analysis and is listed in Table 1 in section 2.2.

2.6 Estimation of slant range errors

As primary radars only calculate the 2D position of an aircraft (range and bearing) the position of an aircraft projected onto a radar display does not represent that actual distance (along the ground) of the aircraft from the radar. This is known as the slant range error.

As the radars are relatively close (not further than 30 Nautical Miles great circle distance) to the site proposed for the Moorshield wind farm we estimated the slant range distance by Pythagorean theorem (i.e. we assumed the Earth to be flat). For this analysis, we did not account for terrain elevation differences and assumed the radars to be at ground level. The slant range error is the difference between the slant range distance and ground distance. This is illustrated in Figure 5.

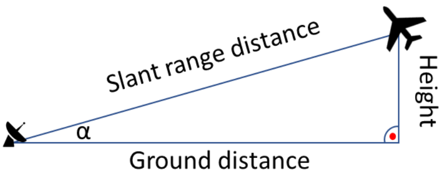

Figure 5: Slant range error can be estimated using Pythagorean theorem

The slant range distance was used to calculate the magnitude of the difference in position reported by the Lowther Hill radar compared to the other analysed radars. The actual position of the aircraft was assumed to be (0,0). The positions of the aircraft reported by the different radars would be offset due to the different slant range errors. The slant range error estimate and the bearing from the radar station was used to determine the coordinates of the aircraft position reported by the individual radars. Finally, the difference between the positions reported by the various radars was determined using Pythagorean theorem. This approach has been illustrated in Figure 6.

[3] AIRAC 2018 06 p.873

[4] Available at: http://www.gov.scot/resource/doc/917/0081425.doc

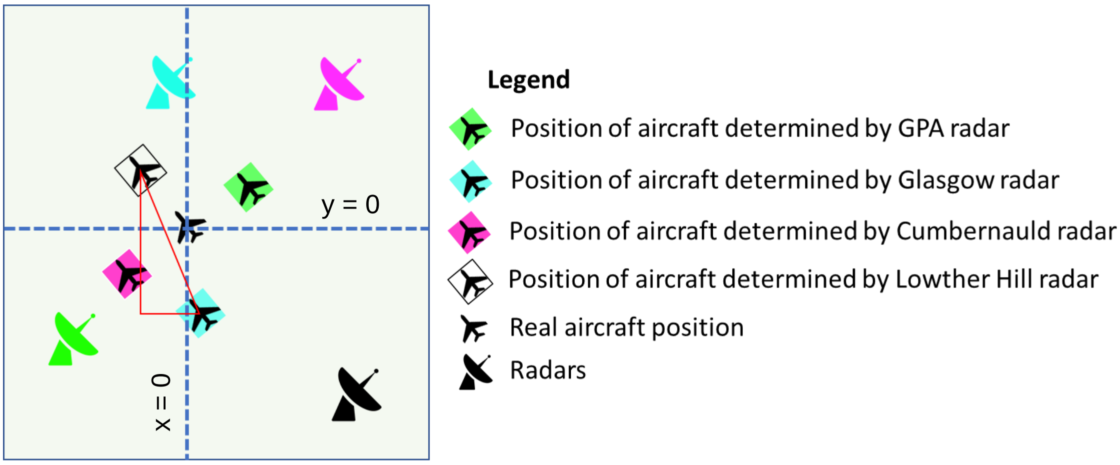

Figure 6: Estimate of difference in the display of an aircraft's position determined by different radars due to slant range error

3 Analysis

3.1 Location of the Moorshield wind farm in relation to the PSRs and other wind turbines

The distance of the Moorshield wind farm from each of the analysed radars is outlined in Table 2 below. The proposed development is surrounded from the South by the already operational Whitelee wind farm, whose turbine tips have a maximum height of 149.9 metres above ground level. The Whitelee wind turbines are located approximately 1200 metres away from the nearest proposed Moorshield wind farm turbines. The distance between neighbouring turbines in the proposed Moorshield wind farm varies between 320 and 530 metres. An overview of the site is shown in Figure 7 and Figure 8.

Radar	Approximate distance from proposed wind farm (NM, km)	Bearing from radar to wind farm (degrees)	Instrumented radar range (NM, km)
Cumbernauld radar	17, 31	216	60, 111
Glasgow Airport Terma Scanter	10, 18	163	40, 74
GPA Terma Scanter	15, 28	31	40, 74
Kincardine	30, 56	225	80, 111
Lowther Hill	29, 53	316	120, 222

Table 2: Relative locations of radars compared to Moorshield wind farm

Figure 7: Map showing the proposed site of the wind farm and radars
(Scale, lower right: 40 km)

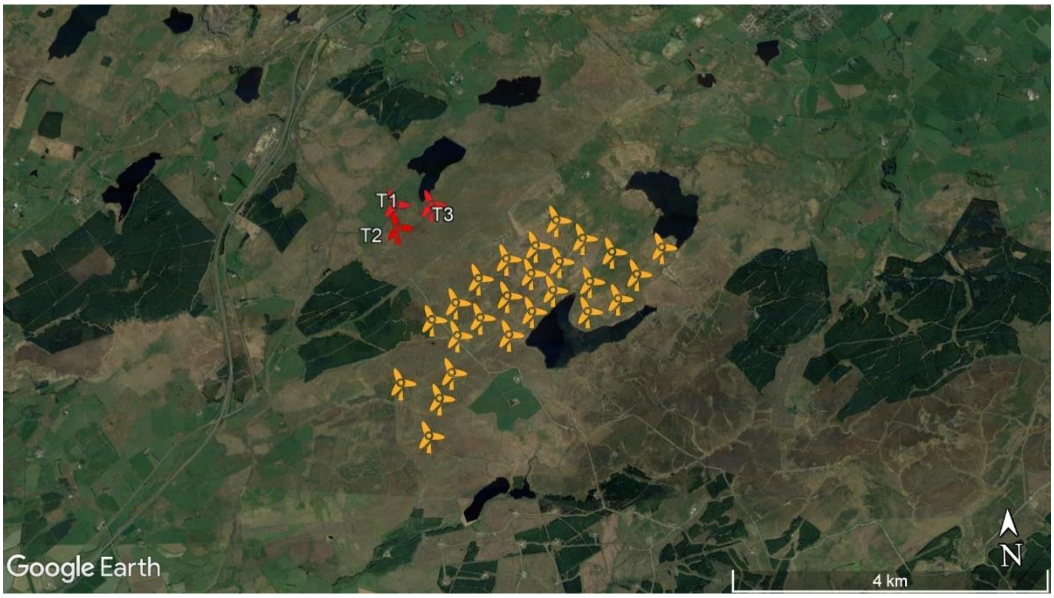

Figure 8: Overview of the proposed Moorshield wind farm site

The 3 turbines of the proposed wind farm are depicted in red, whereas the closest neighbouring turbines of the already existing Whitelee farm are shown in orange.

3.2 Radar coverage analysis

3.2.1 Visibility of the Moorshield wind farm from radar sites

The first step in the analysis was to determine if the 149.9 metre wind turbines of the proposed wind farm would be visible by any of the five radars described above. This was done by conducting visual Line of Sight (LoS) calculations. This is a conservative estimate of the visibility of the radars (i.e. it underestimates the coverage) as it does not account for phenomena such as radio wave diffraction and refraction. These calculations were used to quickly conduct an initial analysis and determine if the wind turbines would be visible to the radars with a high certainty.

Visual LoS calculations completed in Radio Mobile indicate that at a height of 149.9 metres above ground level (the Moorshield turbine tip height) visual LoS would exist at least between parts of the proposed Moorshield wind farm and Lowther Hill and Cumbernauld, Glasgow Airport and GPA. For Lowther Hill visual LoS would extend below 100 metres. Visual LoS coverage at 149.9 metres AGL is depicted for the Lowther Hill, Cumbernauld, Glasgow Airport Terma, GPA Terma and Kincardine radars in Figure 9 to Figure 13. The full length of the scale for Figure 9 to Figure 12 is 10 km and 20 km for Figure 13.

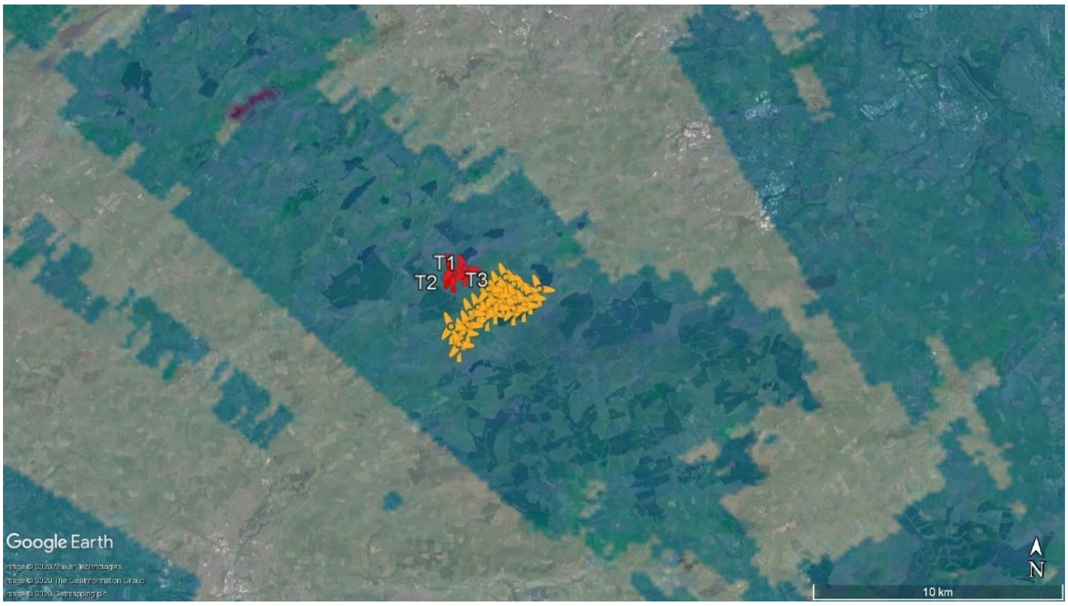

Figure 9: Visual LoS coverage at 149.9 metres AGL from Lowther Hill

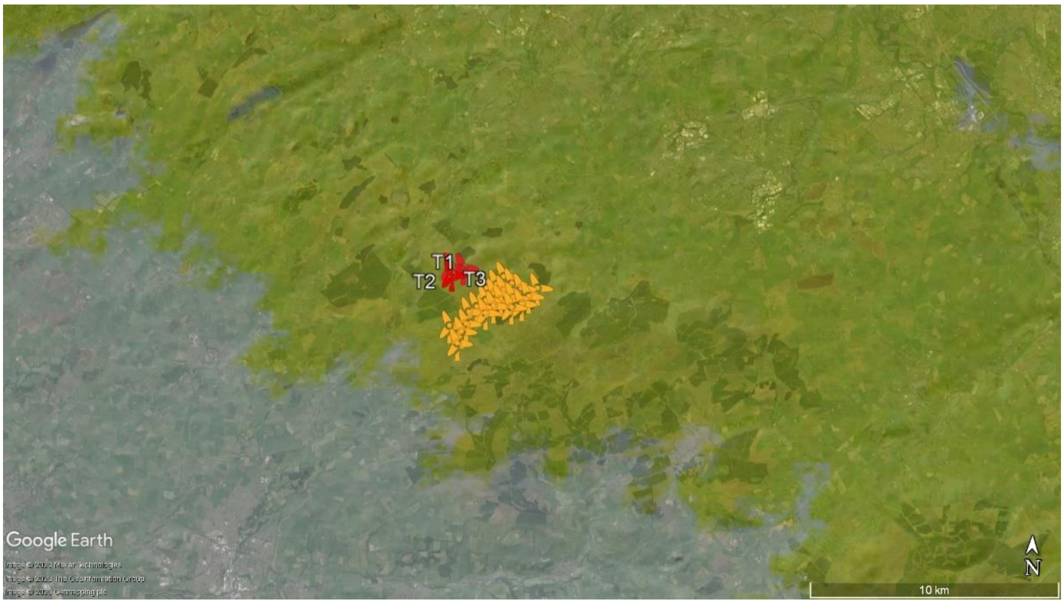

Figure 10: Visual LoS coverage at 149.9 metres AGL from Cumbernauld

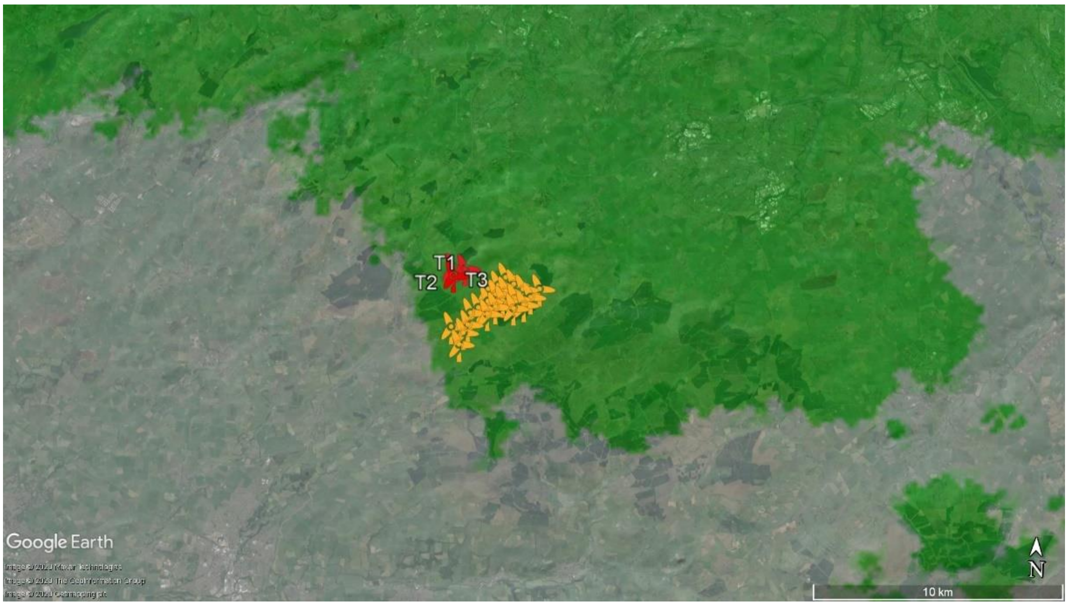

Figure 11: Visual LoS coverage at 149.9 metres AGL from Glasgow airport

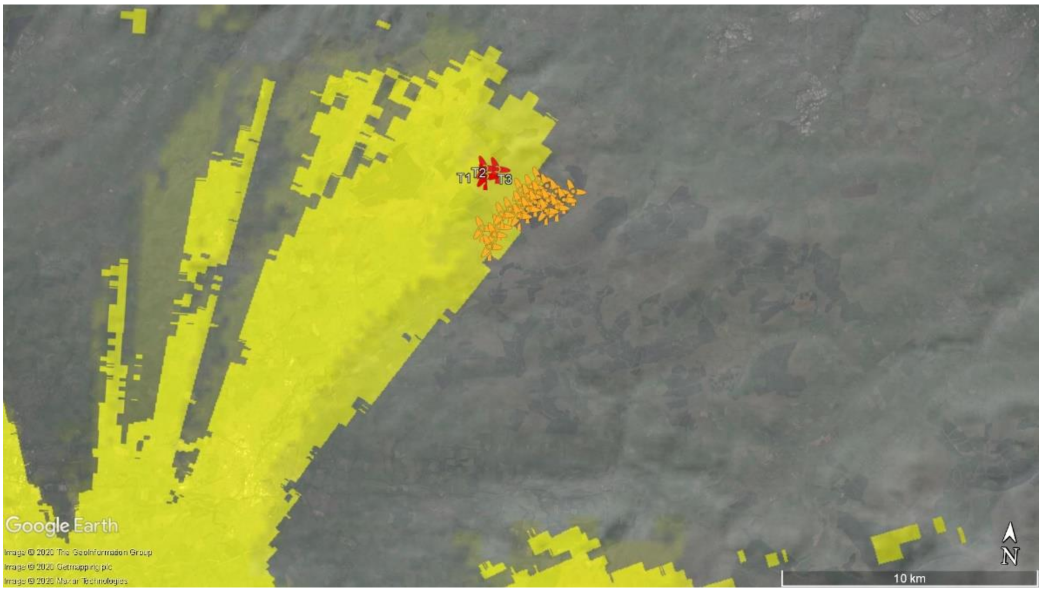

Figure 12: Visual LoS coverage at 149.9 metres AGL from GPA Terma Scanter

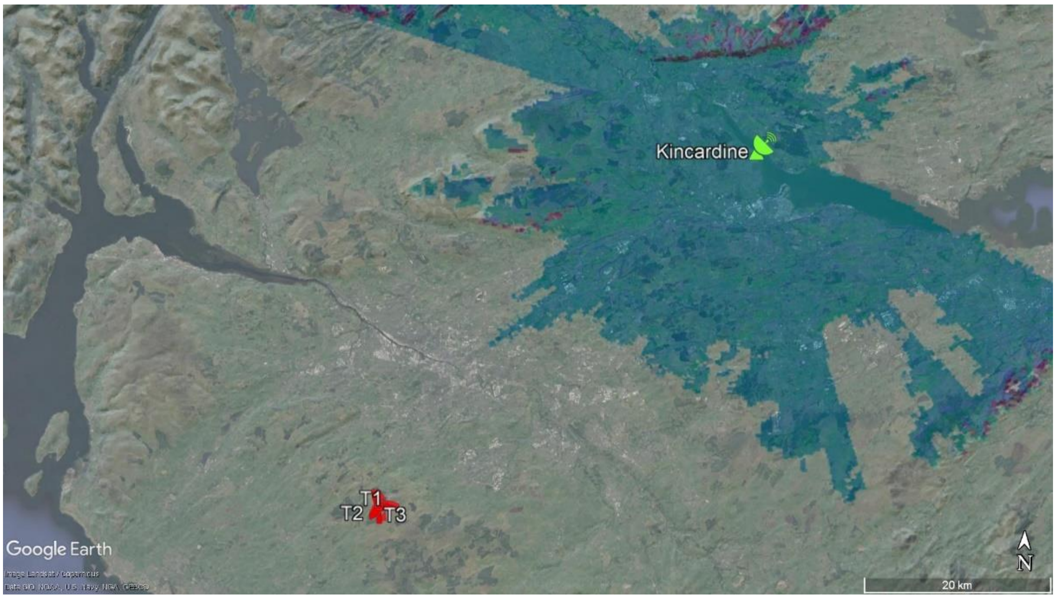

Figure 13: Visual LoS coverage at 149.9 metres AGL from Kincardine radar

The approximate location of the Moorshield wind farm is depicted in red. The Kincardine radar is shown in green. (The full length of the scale is 20 km).

At a height of 149.9 metres AGL the analysis shows that visual LoS with Moorshield would not be present for the Kincardine radar.

For Lowther Hill, Cumbernauld, GPA and Glasgow Airport the analysis shows that Moorshield would be in visual LoS.

To verify the visibility of Moorshield from the analysed radars a more detailed analysis was conducted for Glasgow Airport as well as Cumbernauld, GPA and Kincardine. This is presented in the next section.

3.2.2 Detailed radar coverage analysis

The detailed radar coverage analysis was conducted using the Radio Link profile function in Radio Mobile to display the radio propagation path in a vertical cross-section view between the radar and individual wind turbines. This profile takes into account the effects of 'beam-bending' in radio propagation through the use of a commonly accepted '4/3rds' Earth model[5].

Importance of Fresnel zones

Typically for effective radio signal propagation to take place it is important that no obstructions exist not only within the direct LoS but also within a certain radius of this LoS called the First Fresnel Zone. This radius varies depending on the frequency of the radio waves and distance from the transmitter and receiver and can be established mathematically. Even if LoS is not fully obstructed if sufficiently large obstructions exist within the First Fresnel Zone the radar signal can be strongly inhibited.

Figure 14 to Figure 18 below show the 149.9 metre turbines of the proposed Moorshield wind farm which are potentially most visible from each of the radars. The dashed black and green line depicts the direct radar LoS path[6] and also the shortest LoS path where the direct path is obstructed by the terrain. The white curves surrounding the dashed black and green lines show Fresnel Zones, with the ones closest to the line being the First Fresnel Zones. Note that the diameter of the Fresnel Zones increases with decreasing radar frequency.

The figures confirm that LoS exists for Lowther Hill, Glasgow airport, GPA and Cumbernauld radars. The First Fresnel Zone is not obstructed for these radars and the turbines at the proposed development site.

LoS is completely obstructed for the Kincardine radar.

As shown in Figure 15 to

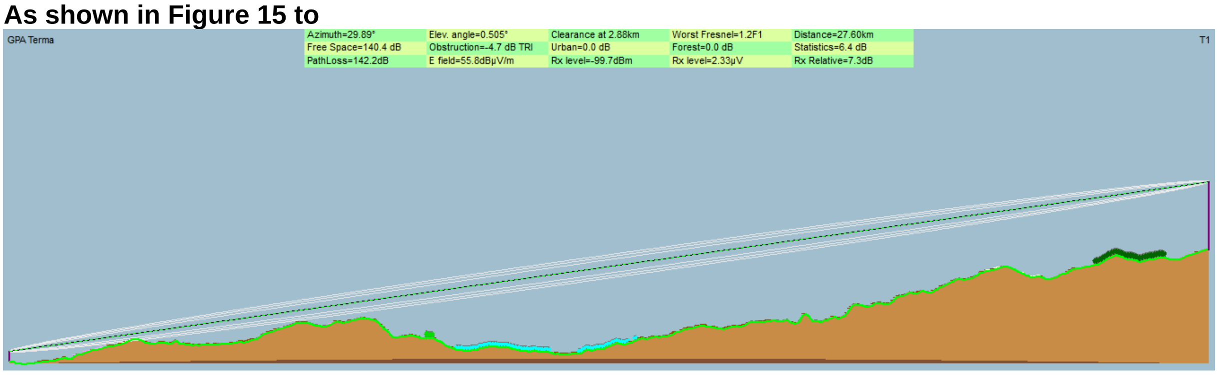

Figure 17 the theoretical radar LoS is at about 1.2, 0.5 and 0.4 degrees above the horizons for the Glasgow, Cumbernauld and GPA radars respectively.

For none of the radars did the angle between it and a target at FL400 above the wind farm exceed 35°. This is illustrated in Figure 19 by the LoS between the Glasgow airport Terma

[5] In this model the Earth's radius is assumed to be 4/3rds the size of the actual average value. This is also known as the k-factor. This has the effect of reducing the effect of the Earth's curvature (flattening the Earth) to account for the fact that at high frequencies (30 Mhz – 30 Ghz) radio waves tend to bend with the surface of the Earth. Note that this is only an approximation and the actual value of the k-factor varies depending on a number of parameters including atmospheric conditions.

[6] Note that radar LoS takes into account the effect of the bending of radio waves (ie using 4/3rds Earth's radius) whereas the visual LoS does not (ie it assumes the average value of the Earth's radius).

Scanter, which is closest to the proposed development, and wind turbine 1 which is the closest to this radar. As none of the other radars is closer to any of the wind turbines the angle between the LoS and the horizon is expected to be the highest in this case, where it is equal to approximately 34.2°. Figure 20 shows a similar profile for the GPA Terma Scanter which is approximately 10 km further from the wind farm site. In this case the elevation angle is approximately 23.4°. Both of these values are within the main part of the expected typical antenna gain pattern and hence both of these radars are expected to be able to provide coverage at FL400 above the wind farm.

In the images below, high urban developments are indicated by red polygons, light blue polygons depict light urban development such as houses whereas green polygons depict areas covered by trees. The different terrain types can also differently affect radar signal strength.

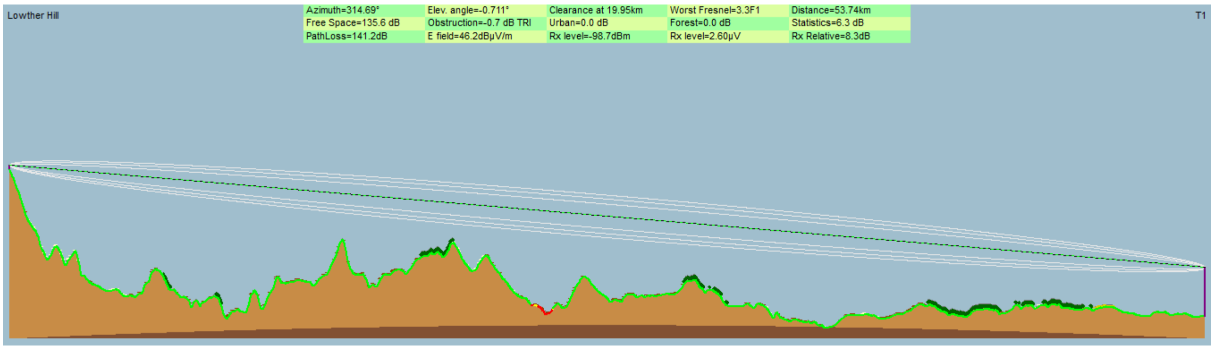

Figure 14: LoS is present between the proposed wind turbines and the radar at Lowther Hill

Here Turbine no. 1 is depicted.

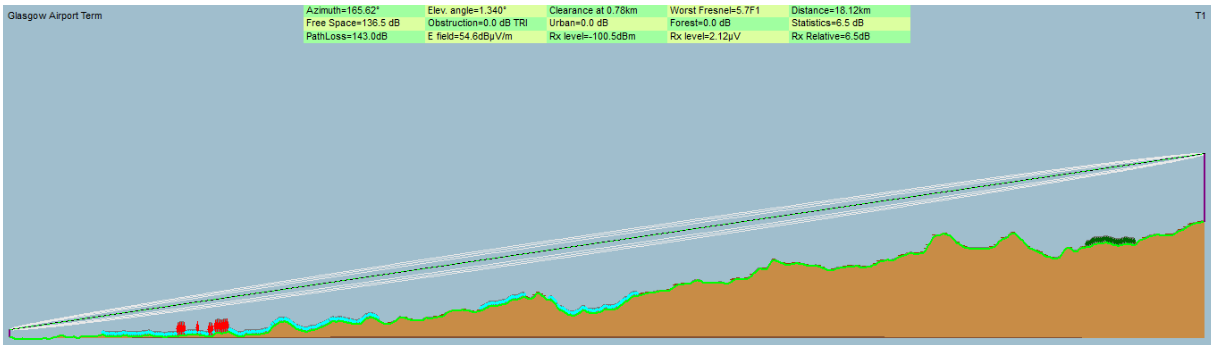

Figure 15: LoS is not obstructed between the proposed wind turbines and the Terma radar at Glasgow Airport

Here Moorshield turbine no. 1 is depicted.

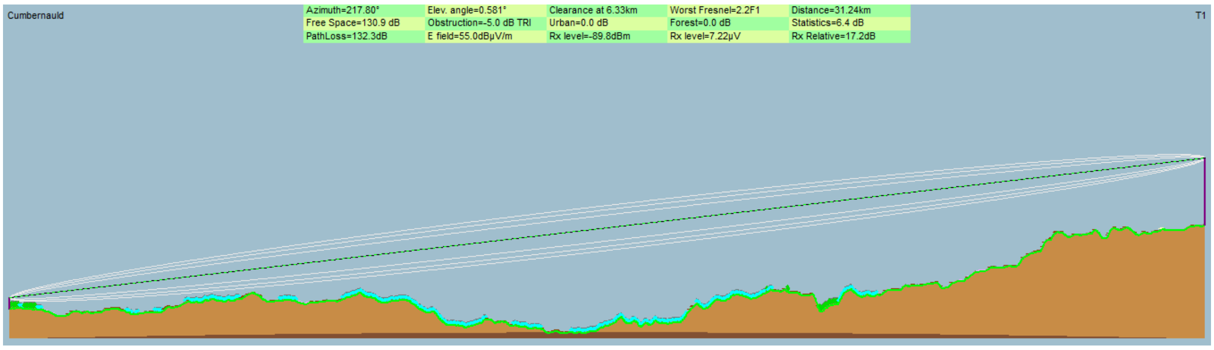

Figure 16: LoS is present between the proposed wind turbines and the radar at Cumbernauld

Here Turbine no. 1 is depicted.

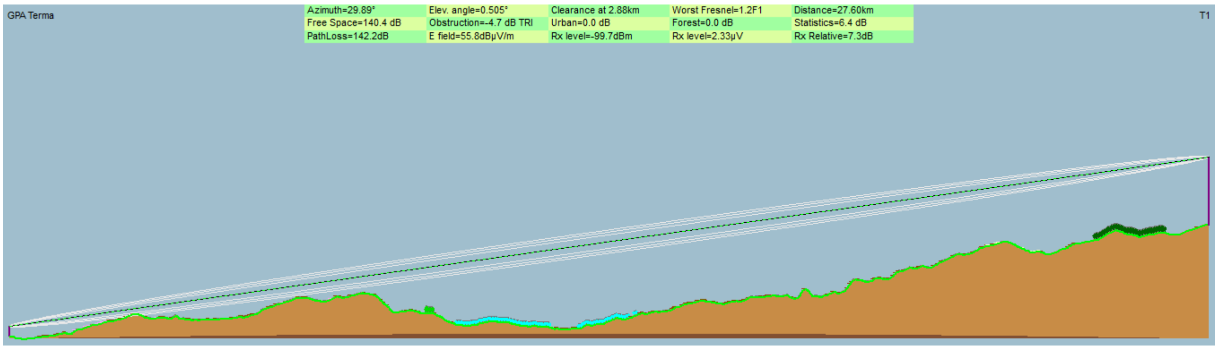

Figure 17: LoS is not obstructed between the proposed wind turbines and the Terma Scanter at GPA

There is direct line of sight to Turbine no. 1, and although there is partial obstruction of Fresnel zones, the First Fresnel Zone is not obstructed.

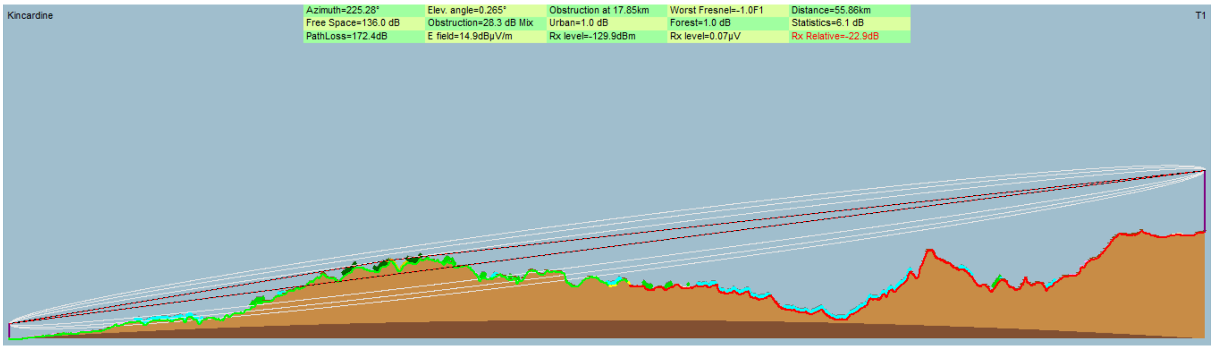

Figure 18: LoS is completely obstructed in F1[7] and F2 between the proposed wind turbines and the Kincardine radar

In this case two dashed black and green lines are present one depicts the direct LoS, whereas the other the direct path which accounts for terrain obstructions. Here Turbine no. 1 is depicted.

[7] F1 – First Fresnel Zone
F2 – Second Fresnel Zone

Figure 19: LoS between the Glasgow airport radar closest to the wind farm and a target at FL400 over Moorshield wind farm

The LoS angle **does not** exceed 35° above the horizon. Here the location of Turbine no. 1 is depicted.

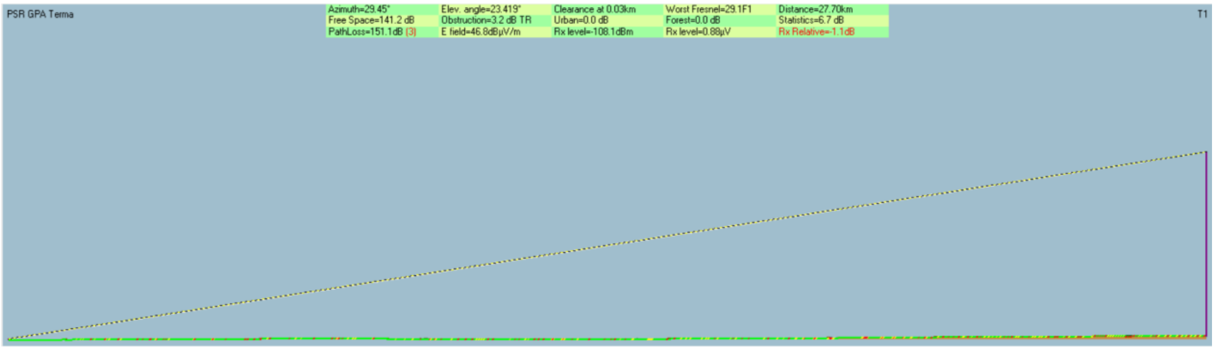

Figure 20: LoS between the GPA radar and a target at FL400 over Moorshield wind farm

The LoS angle **does not** exceed 35° above the horizon. Here the location of Turbine no. 1 is depicted.

3.2.3 Summary - visibility of the proposed wind farm from local radars.

The LoS and radar coverage analysis confirms that Moorshield will be visible to the PSR at Lowther Hill, therefore requiring a solution to mitigate the potential impact of the wind turbine reflections. The analysis also confirms that Moorshield will not be visible to the PSR at Kincardine, which is already used as a radar in-fill mitigation solution for the neighbouring Whitelee wind farm.

The analysis indicates that the Moorshield turbines appear to be in visual LoS of the PSR at Cumbernauld, the Terma Scanter at Glasgow Airport and the GPA Terma Scanter.

The analysis shows that Kincardine cannot see the Moorshield wind farm. The analysis therefore indicates that Moorshield is very unlikely to cause interference to this radar and it is a potential candidate for an in-fill radar if it can provide the coverage required by air traffic controller over the Moorshield wind farm.

Those radar that can see the Moorshield wind farm could potentially still be candidate in-fill radars if they are resistant to the interference effects of wind turbines. The Terma Scanter 4002 is considered more resistant to wind farms than currently installed PSRs. The Glasgow Airport and GPA Terma Scanters are therefore also potential in-fill radar candidates subject to them also providing the required operational coverage over Moorshield. The Terma Scanter 4002 is discussed in section 3.3 below.

3.3 The Terma Scanter 4002 as a radar mitigation solution

The Terma Scanter 4002 has been designed to provide greater resistance to the interference effects of wind turbines compared to existing ATC PSR operating in the S-band or L-band frequency range. The Terma Scanter 4002 was recently installed at GPA and Glasgow Airport specifically as a wind farm mitigation solution that can also provide surveillance radar to support the radar services out to 40 nm. The Terma Scanter 4002 works in the X-band frequency (its operational frequencies are between 8.8 and 9.5 GHz), which enables it to discern targets at a higher resolution compared to L-band and S-band radars. Documented tests indicate that the Scanter radar can reliably distinguish objects between individual wind turbines which are 500 metres apart[8] and it is currently installed as an in-fill solution for the Frodsham wind farm where the approximate turbine space is 300m. The Terma Scanter 4002 is also installed at both Newcastle and Edinburgh airports, as well as in the vicinity of Liverpool John Lennon, and Chester Hawarden, as part of a wind farm mitigation solution[9].

From previous trials a Terma Scanter demonstrator system has been shown to be effective in suppressing the display of false target reports from wind turbines while maintaining a probability of detection of greater than 90%[10] throughout a coverage volume. It should be noted that the evidence in the trials document we have seen shows that the probability of detection directly over the wind farm was closer to 85%[11]. However, we were informed by NATS that the operational system is expected to have a higher resolution and better probability of detection performance than the demonstrator system used in these trials. NATS have also previously stated their confidence in the ability of the Terma Scanter 4002 to achieve a 90% probability of detection performance.

3.4 Coverage above the proposed wind farm

Following the analysis in sections 3.2 and 3.3 the following radars are potential in-fill candidates: Kincardine, GPA Terma and Glasgow Airport Terma.

The next step in the analysis is to look at the ability of each of these radars to provide good coverage of the airspace in which ATC radar-based services are to be provided, and in particular in the en-route airspace that is currently supported by Lowther Hill.

The location of the proposed Moorshield wind farm is below Glasgow CTR Class D airspace present from the surface to 6000 feet ASL and the Scottish TMA Class D airspace from 6000 feet to Flight Level 195 (Figure 21). Above Flight Level 195 the Scottish en-route airspace is present. The Glasgow CTR is controlled by Glasgow airport while the Scottish TMA end en-route airspace is controlled from Prestwick ATCC. Thus, primary radar coverage above Moorshield for use in the Prestwick ATCC should have a minimum level of at least 6000 feet. Ideally the minimum coverage should extend below

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[8] Terma Scanter: "Air Coverage Test with SCANTER 4002 at Horns Rev Wind Farm I and II."
[9] https://www.newcastleairport.com/article/351/
https://www.nats.aero/news/nats-secures-turbine-mitigation-contract-for-tormywheel-wind-farm/
https://www.terma.com/press/news-2016/terma-provides-wind-turbine-mitigation-radar-for-nats/
[10] A typical operational requirement for data from a PSR is greater than or equal to 90% probability of detection over the defined coverage volume.
[11] Windfarm Trial Summary TERMA Radar at Edinburgh Airport, TERMA/EDI/SUMMARY Issue 1, April 2014, NATS

6000 feet to ensure that an aircraft approaching the airspace controlled by en-route controllers would be visible before entering it. Therefore, coverage of each candidate in-fill radar was calculated at an altitude of 5000 ft ASL.

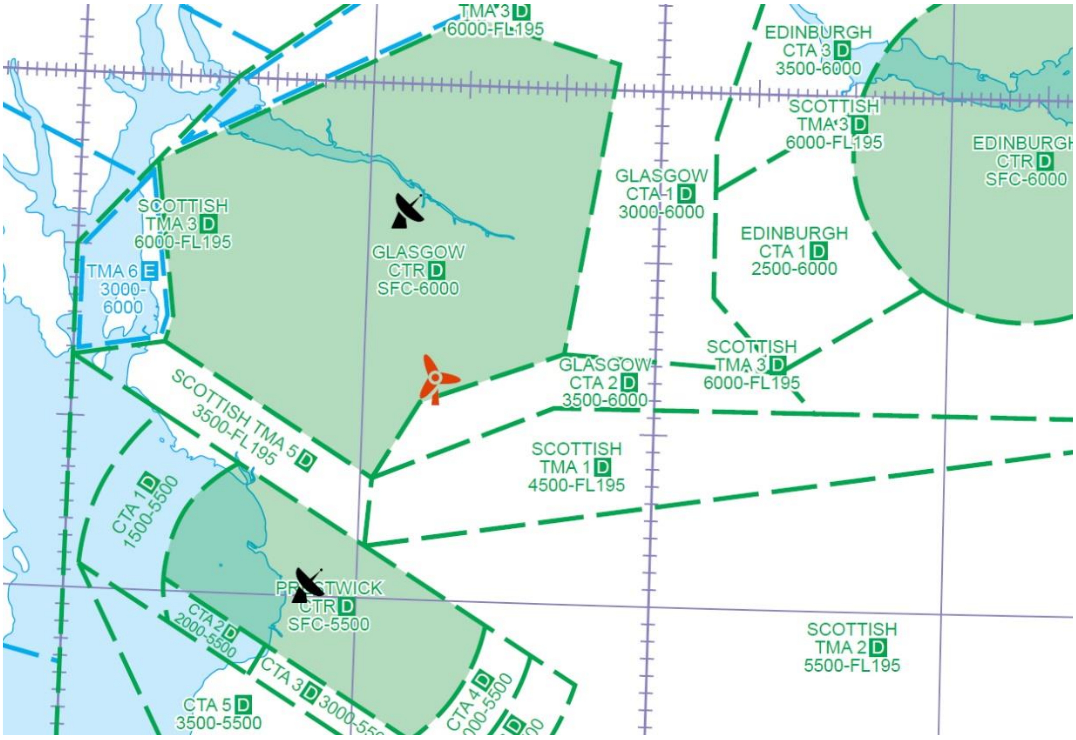

Figure 21: Airspace structure near the proposed Moorshield wind farm

The GPA radar and the approximate location of the Glasgow Prestwick airport is visible in the lower left, whereas the Glasgow airport radar and the location of Glasgow airport are shown in the upper part of the picture. The approximate location of the development is indicated by the red icon in the middle of the figure.

Based on the results of analysis in Radio Mobile and typical radar antenna gain pattern (an example of which is shown in Figure 3) all of the three radars should be able to provide surveillance at the location of the proposed wind farm from 5000 feet ASL. The Terma Scanter radars are expected to be able to provide coverage over the wind farm up to approximately FL400[12]. Kincardine should be able to provide coverage over FL400. Coverage at 5000 feet ASL has been illustrated in Figure 22 through to Figure 24 in which the approximate location of the wind farm is depicted by the red wind turbine icon. The borders of the local Glasgow CTR and CTA airspace have also been depicted. The indicated scale is 30 km.

[12] The expected ceiling limitation for the Terma Scanter 4002 is 40,000 feet. https://www.terma.com/media/253916/wfas-news_2_pdf.pdf

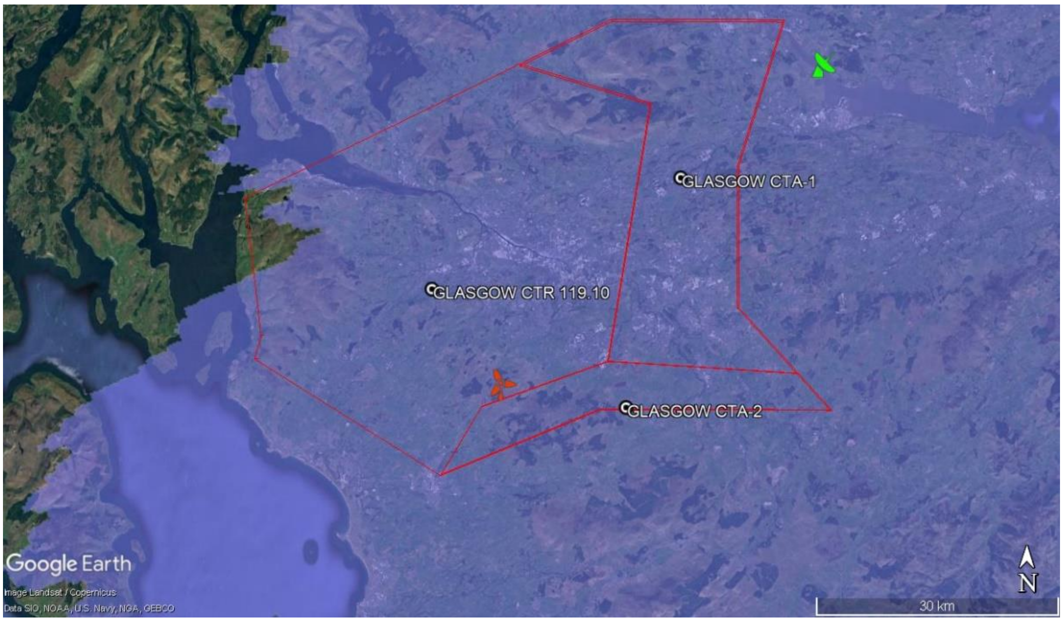

Figure 22: Visual LoS coverage of the airspace above the proposed wind farm by the Kincardine radar at 5000 feet ASL

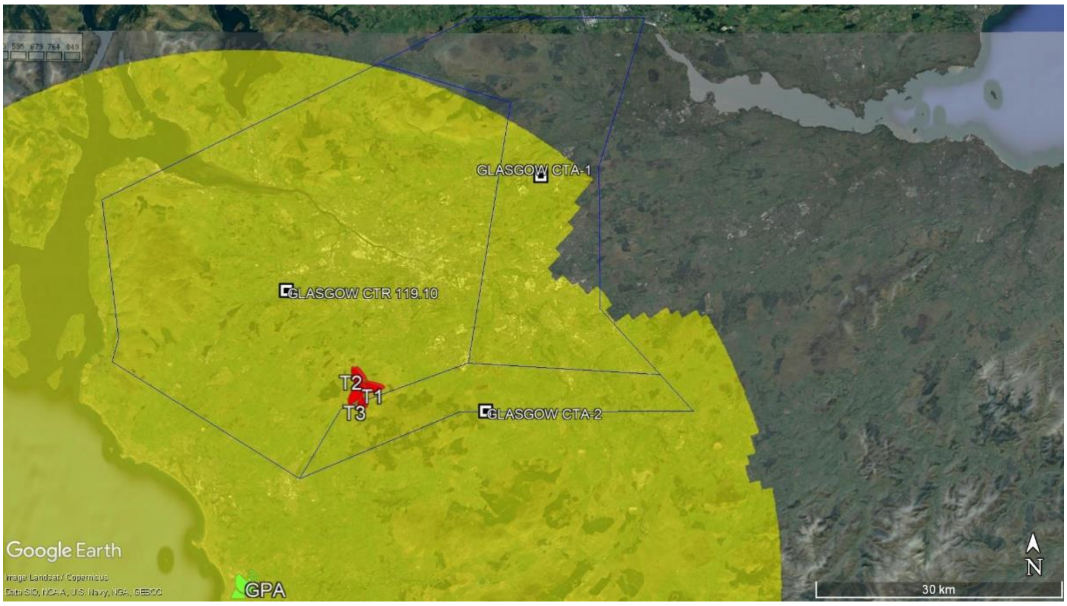

Figure 23: Visual LoS coverage of the airspace above the proposed wind farm by the GPA radar at 5000 feet ASL

Figure 24: Visual LoS Coverage of the airspace above the proposed wind farm by the Glasgow airport radar at 5000 feet ASL

3.5 Accuracy requirements for the coverage above the wind farm

Radar coverage above the proposed Moorshield wind farm is currently provided by the L-band ASR23 (SREM 5) radar located at Lowther Hill. According to NATS' own estimates[13] such a radar can provide the necessary quality of signal to guarantee 3 NM separation up to 80 NM from the radar site (Table 3). 3 NM separation is typically the smallest separation standard applied (i.e. the most demanding on the surveillance infrastructure requirements) and is also often required in busy Terminal Manoeuvring Areas (TMAs).

	Frequency	PSR/PSR Separation Standard		
		3 NM	5 NM	10 NM
En-Route	23cm (L-band)	80	150	160
Approach	10cm (S-band)	50	50	50

Table 3: Distance from radar in NM and separation standard achievable as stated by NATS

[13] Scottish TMA Primary Radar Capability Study. Available at: http://www.gov.scot/resource/doc/917/0081425.doc

Radar accuracy required for 3 NM separation levels.

According to EUROCONTROL Specification for ATM Surveillance System Performance (Volume 1) to maintain 3 NM separation the horizontal position error should not exceed 300 metres; the radar update rate should be less than or equal to 5 seconds and the probability of an update to the horizontal position should be 90%.

No specific accuracy figures have been found for the Terma Scanter 4002. However, the expectation is that as a latest generation ATC radar model its accuracy performance will be at least as good as existing S-band ATC radars. Based on the fact the Moorshield wind farm is only 10 NM from the Glasgow Airport Terma Scanter, and is well within the limits defined in Table 3 above, it is concluded that it would be feasible to use the Glasgow Airport Terma Scanter 4002 to provide a 3 NM separation service within the Prestwick Air Traffic Control Centre. This is further supported by the fact that the Terma Scanter has a higher resolution compared to the S-band radars as described below.

The Terma Scanter 4002 GPA radar utilizes X-band frequencies, which correspond to a wavelength of approximately 2 to 4 cm. The manufacturer states that the radar can provide coverage up to 40 NM and 40,000 feet. The radar has an update rate of four seconds[14]. The higher frequency it uses allows it to achieve a better resolution than the traditional 10cm S-band radars. The manufacturer indicates that the Terma Scanter 4000 series radar can achieve a range resolution of up to 12 metres[15]. This is better than the typical range resolution of a 10 cm radar which can be estimated at 50 metres[16]. In tests the radar was further able to clearly discern individual wind turbines separated from each other by approximately 500 meters and aircraft flying over the wind farm when situated at a distance of 7.5 NM from the wind turbine site[17]. It should be noted that both azimuth resolution and accuracy will decrease within increasing range from the radar.

NATS states that for a typical 10 cm approach radar 3 NM separation can be provided to 50 NM. The Moorshield wind farm is only 10 NM from the Glasgow Airport Terma Scanter. The Terma Scanter is also closer to the proposed wind farm than both the Cumbernauld and Kincardine radars and thus even if it was a 10 cm S-band radar it would be expected to provide more accurate surveillance reports than the other proposed in-fill radars.

3.6 Slant range error assessment

This section analyses the potential slant range errors that could result in a discontinuity in the radar track displayed to a controller in the Prestwick en-route Air Traffic Control Centre as an aircraft passes across the Moorshield wind farm when in-fill data is combined with data from Lowther Hill.

PSR calculate the 2D position of an aircraft as a slant range and bearing from the radar. A PSR does not calculate the height of the aircraft although the height can be derived from other sources (e.g. secondary surveillance radar). The slant range is the distance travelled by the radio wave between the radar and the aircraft and is greater than the great circle distance to the aircraft position projected on to the Earth's surface. The slant range error is the difference between these two distances. The slant range error will therefore increase

[14] Terma brochure: https://www.terma.com/media/253916/wfas-news_2_pdf.pdf

[15] IEEE 2011: "Air Traffic Control at Wind Farms with TERMA SCANTER 4000/5000".

[16] http://www.indracompany.com/sites/default/files/12_psr_brochure_v1_02-2009_eng.pdf

[17] Terma Scanter: "Air Coverage Test with SCANTER 4002 at Horns Rev Wind Farm I and II."

for an aircraft at a given location on the Earth's surface as its height increases. The slant range error also means that when data from two different radars is shown on the same display (and therefore converted into a common coordinate reference system) an aircraft will be shown at different locations by each radar. The difference between these positions will depend on the distance of the aircraft to each radar, the height of the aircraft and the relative geometries of the radar. This is illustrated in Figure 6 and Figure 25.

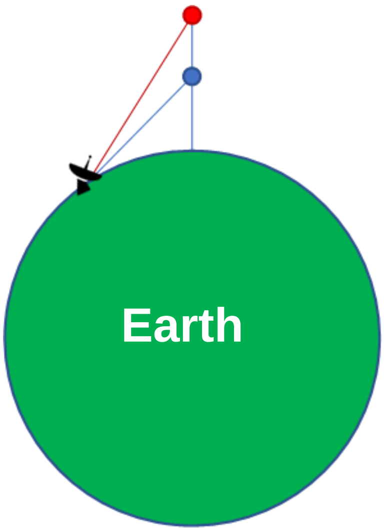

Figure 25: Different slant ranges for an aircraft at the same location but different heights

The distances between the Glasgow Airport, Cumbernauld, GPA and Kincardine radars and the site of the wind farm are 10, 17, 15 and 30 NM respectively while the distance between the Lowther Hill radar and the proposed wind farm site is 29 NM. These along with the bearings from the stations are summarised in Table 2.

The calculated slant range errors associated with each of the radars for an aircraft located over the Moorshield wind farm are summarised in Table 4. This table also summarises the difference in the displayed position between each of the proposed in-fill radars and Lowther Hill (i.e. the magnitude of the discontinuity in the radar track that would be shown on a controller's display as the aircraft moves from an area supported by Lowther Hill data to an area supported by the in-fill radar).

Description	GPA Terma	Glasgow Airport Terma	Kincardine radar	Lowther Hill radar
Ground distance between radar and proposed wind farm (NM)	15	10	30	29
Elevation of aircraft at 5000 feet ASL (1524 metres)	3.1°	4.7°	1.6°	1.6°
Elevation of aircraft at 40,000 feet ASL (12192 metres)	23.8°	33.4°	12.4°	12.8°
Slant range error 5000 feet (NM)	0.02	0.03	0.01	0.01
Slant range error 40,000 feet (NM)	1.39	1.98	0.72	0.74
Difference in displayed aircraft position in NM between radar and Lowther Hill radar at 5000 feet ASL	0.02	0.04	0.02	0
Difference in displayed aircraft position in NM between radar and Lowther Hill radar at 40,000 feet	1.39	2.66	1.04	0

Table 4: Different in displayed position due to slant range errors for in-fill radars

Table 4 shows that the slant range errors are uncorrected the discontinuity in the displayed aircraft position for the Glasgow Airport Terma Scanter compared to Lowther Hill will be between 37 metres and 2.66 nautical miles between 5000 and 40000 feet ASL. This is slightly more than for the GPA Terma Scanter. Kincardine has the lowest slant range error. A one nautical mile discontinuity would be noticeable to a controller on a display. In addition, the Eurocontrol ATM surveillance specification specifies that to provide 3 NM separation the horizontal position error must be less than 300 metres. It is therefore highly likely that all potential in-fill radars will need some form of slant range error correction applied for aircraft at high altitude.

The Prestwick ATCC uses a Multi Radar Tracker (MRT) to calculate the best estimate of the position of an aircraft by combining data from multiple radar sources, including secondary radars that provide aircraft altitude information. The algorithms in the MRT are typically configured to weight the calculation of the position towards the radar sensors assessed to provide the highest quality position data. In addition, where altitude data is available for an aircraft this can be used to correct slant range errors. NATS is also known to already use inputs from regional airport PSRs into its MRT at Prestwick ATCC. Therefore, within the MRT solution implemented in Prestwick ATCC any potential slant range errors associated with an in-fill solution are expected to be manageable.

3.7 Configuring a Terma Scanter 4002 for wind farm mitigation

If a Terma Scanter 4002 radar is to be used as an in-fill radar for a wind farm that is within LoS additional assessment steps may be required to ensure that the specific radar will be able to provide sufficient mitigation against the interference from the wind farm.

Based on information provided by Glasgow Prestwick Airport in response to a planning application appeal the following steps may be required.

Firstly, a feasibility assessment may need to be carried out in order to assess whether or not the specific radar has the technical capability and capacity to mitigate the adverse effects caused by a particular wind farm. This is a desktop based exercise which involves detailed radar modelling of the proposed windfarm topographical layout, turbine nacelle height and shape, blade diameter and maximum tip height against the radar performance characteristics and signal processing capabilities of the Terma Scanter 4002 X-Band Radar.

If the feasibility assessment positively confirms that the radar system has the technical capability and capacity to mitigate the wind farm, then configuration work would need to be carried out on the radar system in order to adapt and modify the system so that it can mitigate the wind farm. The configuration work includes (amongst other things);

- radar modelling
- radar optimisation in the airspace above the relevant wind farm
- flight trials over the wind farm airspace, if necessary, depending on topography and other factors
- population, validation and updating system documentation and procedures to account for the mitigation
- potential modification of air traffic control procedures and documentation
- population, validation and updating of safety case documentation and submission and obtaining of CAA approval where required.

4 Conclusion

The analysis confirms that the planned Moorshield wind farm will be visible to the NERL Lowther Hill PSR used to support surveillance based Air Traffic Service in the Prestwick ATCC. This will very likely result in interference to Lowther Hill and a mitigation solution will therefore be required.

The new Terma Scanter 4002 at Glasgow Airport (operational since early 2019) has been proposed as an alternative in-fill solution in place of Kincardine to mitigate the impact of the Moorshield wind farm on Lowther Hill.

The analysis confirms that Kincardine is a potential in-fill option as the Moorshield wind farm is screened by terrain and will therefore not provide interference to Kincardine. However, Kincardine can still provide full coverage of the Scottish TMA controlled airspace above Moorshield and should therefore meet the operational requirements of the controllers in the Prestwick ATCC.

The Moorshield wind farm is visible to the Terma Scanter 4002 at Glasgow Airport. This could potentially result in interference except that the Terma Scanter is known to provide increased resistance to the interference from wind turbines while maintaining aircraft detection performance. The Terma Scanter 4002 has also been installed, or is in the process of being installed, specifically as a wind farm mitigation solution at a number of airports in the UK, such as Newcastle, Edinburgh, and Liverpool John Lennon. The analysis shows that the Glasgow Airport Terma can provide full coverage of the Scottish TMA controlled airspace above Moorshield. The Terma Scanter 4002 at Glasgow Airport may therefore be a potential in-fill option for Moorshield subject to a more detailed feasibility assessment to be carried out by the installers and operators of the system.

Similar to Glasgow Airport the Terma Scanter 4002 installed at GPA may also be a potential in-fill option. While the turbines will be visible to the GPA Terma, the Terma Scanter should provide increased resistance to this interference subject to a more detailed feasibility assessment, and appropriate configuration, by the installers and operators of the system. The analysis also shows that the GPA Terma can provide full coverage of the Scottish TMA controlled airspace above Moorshield.

The accuracy and resolution of the Glasgow Airport and GPA Terma Scanters are expected to be as good as or better than that of existing S-band PSRs installed at Kincardine and Cumbernauld. The Glasgow Airport and GPA radar are also closer to Moorshield than Kincardine. Therefore, using a NATS Scottish TMA Primary Radar Capability Study assessment from 2009 as a reference source, it is concluded that the accuracy of the GPA and Glasgow Airport Terma Scanters should be sufficient to be used as an in-fill data source to support 3 NM separation within the Prestwick en-route Air Traffic Control Centre.

Slant range errors associated with combining a second source of primary radar data for an in-fill area with the main source of primary radar data is not expected to be a significant problem in a Multi Radar Tracker surveillance solution such as that implemented in the Prestwick ATCC.

Therefore, it is concluded that Kincardine, Glasgow Airport Terma and GPA Terma are all potentially feasible technical radar mitigation solutions for the Moorshield wind farm.

A Planned coordinates of Moorshield wind turbines

The coordinates and planned height AGL in metres of the components of the 3 planned wind turbines of Moorshield wind farm are listed below.

No	Easting	Northing	Longitude	Latitude	Hub	Tip
1	251621	649554	-4.363584	55.716629	81.9	149.9
2	251643	649212	-4.363065	55.713835	81.9	149.9
3	252108	649522	-4.355821	55.716491	81.9	149.9

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