



THE EFFECTS OF WIND TURBINE FARMS ON AIR DEFENCE RADARS

AWC/WAD/72/652/TRIALS

6 JAN 05

OPEN REPORT

THE EFFECTS OF WIND TURBINE FARMS ON AIR DEFENCE RADARS

EXECUTIVE SUMMARY

1. The UK Government supports the introduction of wind turbine farms as part of its alternative energy strategy but existing Ministry of Defence (MoD) Guidelines restrict planning consent for wind turbine farms within 60% of maximum instrumented range (interpreted as 74 km) and line of sight from primary surveillance radars. However, wind farm developers are increasingly questioning the validity of current Guidelines. Consequently, a Trial was conducted by the Air Command and Control Operational Evaluation Unit (Air C2 OEU) in response to a tasking from the Directorate of Counter Terrorism and United Kingdom Operations (D CT&UK Ops) to determine the effects of wind turbine farms on Air Defence (AD) radars. Stage 1 of the Trial was a scoping exercise conducted during the period 28 - 29 Jul 04. A Type 101 (T101) Radar deployed to RAF Church Fenton and utilised the Ovenden Moor wind turbine farm. A Chinook HC Mk 2 and a Tucano T Mk 1 aircraft each provided a single sortie in support of Stage 1. Stage 2, the full Trial, was conducted over the period 14 - 16 Sep 04 utilising the Llandinam (P&L) wind turbine farm in South Wales. The T101 was deployed to a privately owned site in Shropshire, adjacent to the National Air Traffic Services (NATS) radar site at Clee Hill. Sorties in support of Stage 2 were flown by Hawk T Mk 1a, Tucano T Mk 1, Dominie T Mk 1a and a King Air aircraft operated by Flight Precision Limited (FPL). Specialist support was provided by personnel from the Directorate of Engineering, Interoperability & Information Systems (DEI&IS), Defence Science and Technology Laboratory (DSTL) and AMS, the manufacturer of the T101.
2. The aim of the Trial was to determine the effects of wind turbine farms on AD radars by considering the effects of wind turbine farms on radar performance with regard to probability of detection, tracking and displayed effects, the effects on low-level coverage due to the wind turbine farm and system set-up and observed displayed effects. This was achieved by tasking scripted sorties with a variety of aircraft types to overfly the subject wind turbine farm. The radar video display was assessed during the trial and radar plot data was captured for analysis.
3. Previous research had predicted a shadow region behind the wind turbines within which primary radar responses would be masked; this was confirmed by this Trial. Clutter due to the wind turbines was displayed throughout the Trial. During this Trial the observed effect was not operationally significant; however, as many variables (including: radar type, turbine parameters, location and weather) impact on levels of displayed clutter, this observation does not automatically read across to other situations. Observations during Stage 1, indicated aircraft obscuration overhead wind turbines. This effect was examined in depth during Stage 2. **It was confirmed that on the T101 radar, primary radar returns from aircraft having a low Radar Cross Section (Hawk T Mk 1a and Tucano T Mk 1) are lost when flying over wind turbines, regardless of the aircraft's height. The cause of this effect is believed to be as a result of excessive**

returns from the wind turbines being received in the elevation sidelobes of the radar. As a result of this Trial, the MoD has provisionally ceased automatic approval of wind turbine developments beyond 74 km but within Line of Sight from an AD radar.

OPEN REPORT

THE EFFECTS OF WIND TURBINE FARMS ON AIR DEFENCE RADARS

INTRODUCTION

4. The UK Government supports the introduction of wind turbine farms as part of its alternative energy strategy. The existing MoD Guidelines restrict planning consent for wind turbine farms within 60% of the maximum instrumented range (interpreted as 74 km) and line of sight of primary surveillance radars. Both the wind turbine farm developers and the Royal Society have challenged the validity of these restrictions. Consequently, D CT&UK Ops tasked the Air C2 OEU with determining the effects of wind turbine farms on AD radars.

5. Stage 1 of the Trial was a scoping exercise conducted over the period 28-29 Jul 04. Stage 1 utilised the Ovenden Moor wind turbine farm and a T101 Radar, deployed to RAF Church Fenton. A Chinook HC Mk 2 and a Tucano T Mk 1 aircraft each provided a single sortie in support of this Stage. Stage 2, the full Trial, was conducted between 14 - 16 Sep 04 utilising the P&L wind turbine farm in South Wales. The T101 radar was deployed to a privately owned site in Shropshire, slightly below the NATS radar site at Clee Hill. Hawk T Mk 1a, Tucano T Mk 1, Dominie T Mk 1a aircraft and a King Air aircraft operated by FPL, flew sorties in support of Stage 2. The Trial Management Officer (TMO) for Stage 1 was Flight Lieutenant (Flt Lt) Smith. Flt Lt Middleton assumed TMO duties for Stage 2. Additional specialist support was provided by personnel from the DEI&IS, DSTL and AMS, the manufacturer and Design Authority for, the T101.

AIM

6. The aim of the Trial was to determine the effects of wind turbine farms on AD radars.

TRIAL OBJECTIVES

7. The objectives of the Trial were to:

a. Determine the adverse effects of wind turbine farms on radar performance with regard to:

- (1) Probability of Detection.
- (2) Tracking.
- (3) Displayed effect.

- b. Provide a prediction on the effects of low-level coverage due to the wind turbine farm.
- c. Provide guidance on system set-up and observed displayed effects.

CONDUCT OF TRIAL

8. Stage 1 of the Trial was used as an information gathering exercise due to the lack of knowledge within the AWC and DSTL about the effects that windfarms have on radars. This was intended to provide sufficient data to scope the design of Stage 2, which was to be the major stage of the Trial. Stage 2 was designed to ensure that sufficient data was gathered to enable the AWC to provide advice to the sponsor on the impact of generic wind turbine farms on a representative in-service AD radar.

EQUIPMENT UNDER TEST

9. The equipment under test was a T101 radar. Due to time constraints, clearance to radiate Secondary Surveillance Radar (SSR) from the T101 trial deployment site was not obtained for Stage 1 but was obtained for Stage 2. As the Trial was primarily designed to investigate the effect of a wind turbine farm on primary surveillance radar this did not impact on the validity of the Trial. The wind farms evaluated during the Trial were as follows:

- a. Stage 1 – Ovenden Moor, Yorkshire. The Ovenden Moor wind turbine farm was commissioned in Jun 93 and comprises 23 Vestas Type 400 turbines. Data on turbine orientation and performance was not collected during Stage 1. The Radar to wind turbine farm range was 49 km.
- b. Stage 2 – P&L Wind Turbine Farm - Wales. The P&L wind turbine farm was commissioned in Jan 93 and comprises 103 Mitsubishi Type 300 turbines. Turbine data collected during Stage 2 is at Annex A. The radar to wind turbine farm range was 57 km.

TRIAL METHOD

10. The impact from wind turbines on AD radar was expected to take 3 forms, which are as follows:

- a. Clutter. It was anticipated that the Doppler effect of the rotating turbine blades would cause unwanted primary radar returns known as clutter. Previous ATC-centric trials had regarded clutter resulting from wind turbines as a key issue.
- b. Shadow. The presence of a physical obstruction with a large Radar Cross Section (RCS) in the path of the radar beam was expected to create a region behind the turbine farm within which aircraft would be masked from detection. Theoretical modelling suggested that this region would only be a few km deep.

c. Tracking Interference. Both the presence of clutter and the loss of radar returns due to shadowing were expected to interfere with the ability of the system to initiate and maintain a track on target aircraft.

11. Stage 1 Sorties. Two sorties were tasked, the minimum deemed necessary to explore the phenomena listed in para 10. Given the slow rotation rate (6 rpm) of the T101 radar and the relatively small size of the wind turbine farm, it was necessary to choose aircraft capable of sustained and stable flight at slow speed, ideally sub-200 kts ground speed. This would maximise the valid data gathered for each aircraft. Therefore, a Chinook HC Mk 2 and a Tucano T Mk 1 aircraft were each tasked to fly a single sortie. The sorties required the aircraft to operate in a figure-of-eight pattern behind the wind turbines at a height selected to place them in the expected shadow region of the turbines.

12. Stage 2 Sorties. Having confirmed the presence of a shadow region behind the turbines during Stage 1, the sorties flown in support of Stage 2 were required to further explore the bounds of this effect. Having proved successful in Stage 1, the Tucano T Mk 1 and Chinook HC Mk 2 aircraft were tasked to fly one and 2 sorties respectively. An ad hoc observation of an overflying, non-participating, aircraft during Stage 1 had indicated an overhead obscuration effect directly above the wind turbine farms. Therefore, an additional profile was incorporated to further explore this problem and a Hawk T Mk 1a aircraft was tasked in support of this. In order to ensure that the data gathered from the Trial was robust, a wide range of targets with a variety of Radar Cross Section (RCS) were required. It was highly desirable to have Global Positioning System (GPS) positional data available from the trials aircraft for detailed post-trial analysis. For both of these reasons, a Dominie T Mk 1a aircraft was tasked to augment the sorties already scheduled. Finally, DEI&IS was closely involved in the design of the Trial, as the agency initially tasked with its conduct. They volunteered the use of a King Air aircraft that was normally tasked to conduct routine radar calibration sorties. Consequently, the King Air aircraft offered the potential for extremely accurate sortie profiles to be flown and therefore detailed analysis of the observed effects. The basic flight profiles are detailed at Annex B.

13. Data Recording. The effect of displayed clutter resulting from a wind turbine farm was assessed visually at the operator's video output. Unfortunately, there was no available facility to record that output directly on the T101 and there was no funding available to support the installation of additional hardware for that purpose. Therefore, it was decided, for Stage 2, to employ a conventional video camcorder to capture the video output as presented to the T101 operator. A far more comprehensive form of data capture was necessary to support post-trial analysis of the radar plot picture. Therefore, DEI&IS was requested to provide Radar Data Console (RADAC) data capture hardware and subsequent analysis of the data. The RADAC recorded all the extracted plot data produced by the radar, in the same format that it would be input into the UKASACS Command and Control System (UCCS).

TRIAL CONSTRAINTS

14. The following constraints applied to the Trial:
- a. Due to the nature of this Trial it was necessary to observe a wind turbine farm in line of sight of an AD radar. The MoD routinely objects to the development of any wind turbine farm expected to interfere with a static AD radar. Therefore, it was necessary to use a deployable AD radar, limiting the choice to the T101. Moreover, the deployment site had to be suitable for the T101 support vehicles, permit radiation of both primary and secondary radar and be within line of sight of a wind turbine farm. The choice of site was thus limited.
 - b. Funding restrictions and radar availability required the Trial to be conducted during the week when the T101 was en route to a pre-planned exercise. This constrained the preparation time for the Trial and the choice of trial dates.
 - c. An upper height restriction of 24 000 ft was imposed on the Trial at the request of the participating aircrew during the planning stages. This height was significantly above any expected interference effect from the wind turbines.

TRIAL RESULTS

15. Non-Effective Sorties. The planned Chinook HC Mk 2 aircraft sortie in support of Stage 2 was cancelled due to aircraft unserviceability. The reserve sortie was not flown due to higher priority tasking. However, all other sorties were flown as planned and sufficient data was obtained to support valid conclusions.
16. Overhead Obscuration. The most significant operational effect observed during the Trial was the obscuration of aircraft flying directly overhead the wind turbine farm. This effect had not been anticipated in the initial design of the Trial and was first observed during an ad hoc overflight of the Stage 1 wind turbine farm by a non-participating aircraft. Therefore, the sortie profile flown by the Hawk T Mk 1a aircraft during Stage 2 was deliberately planned to investigate this problem up to a height of 24,000 ft, well in excess of the expected upper limit of any obscuration. Further serials were added where Dominie T Mk 1a and Tucano T Mk 1 aircraft profiles were used to confirm the data collected from the Hawk sortie and investigate the relevance of target aircraft RCS. The T101 radar was observed to lose primary radar contact on the low RCS aircraft, Hawk and Tucano, when they were overhead the wind turbines. This loss of contact occurred regardless of aircraft height. Sample RADAC output demonstrating the loss of primary radar returns during the Trial is at Annex C and a proposed explanation of this effect is at Annex D. There is no evidence to support the existing assumption that this, or any other effect of wind turbines on primary radar is range dependent. Current MoD guidelines allowing wind turbine development outside 74 km range from the radar would not mitigate this problem. Conversely, there is no range within which objection to a wind turbine development should be automatic. Based on the

information available at the completion of this Trial, the relevant factor for consideration would be line of sight between the radar and the wind turbines. The presence of a gap in primary radar coverage over wind turbine farms has a potential impact on both AD operations and the provision of Air Traffic Services (ATS). Therefore, **it is recommended that:**

- a. **Automatic approval of wind turbine farms based on ranges beyond 74 km ceases.**
- b. **The potential impact of any wind turbine farm within radar line of sight of an AD radar, regardless of range, be closely examined.**
- c. **Personnel using AD radars in support of the provision of ATS be informed that they are likely to lose primary radar returns over wind turbine farms and should consider limiting the radar services they offer accordingly.**
- d. **Accurate positional data for UK wind turbine farms is made available to personnel using AD radars to support the provision of ATS.**

17. Shadow. An analysis of the plot data recorded by RADAC clearly demonstrated the presence of a shadow region behind the wind turbine farm. This data is shown graphically at Annex C. The vertical limits of this shadow region were assumed to be a linear effect as with the conventional shadow effect observed when a radiating light source is placed in front of a physical obstruction. Consequently, no data was gathered from which the vertical extent could be determined. This shadow region is believed to be a direct result of the interference of large physical objects, components of the wind turbine towers, with the propagation of the radar beam. It should only occur in the region immediately behind the turbines, as indicated at Annex E. A more detailed analysis of the bounds of the shadow region will be available in a separate report to be issued by DEI&IS. Given the low altitudes involved, less than 5000 ft inside likely radar line of sight, ATS would not routinely be provided by AD controllers to aircraft inside the shadow region. Nonetheless, there remains an operational impact on the detection of low-level target aircraft. However, given that the shadow effect is bounded to a few km and assuming that it is only present at low-level, it can be mitigated through the employment of overlapping radars, limits on size and location of wind farms and the long range detection of targets using other assets. These options are discussed in more depth at Annex E. **It is recommended that the cumulative impact of wind turbine farm developments be considered with regard to limiting the number and size of shadow regions in close proximity to each other.**

18. Radial Wind Turbine Farm Developments. It has been suggested that wind turbine farms be developed on a radial to AD radars in those cases where they fall within radar line of sight. This would have the benefit of reducing the number of turbine blades visible to the radar. However, there is very little theoretical understanding or practical experience of how radar beams are affected by physical obstructions of this nature. The AWC is currently unable to predict how an extended radial development of wind turbines

will impact on the ability of the radar beam to reform. It remains possible that a radial development may have a negative impact on overall operational effect. Future study would be necessary in order to understand this problem. Independent advice from AMS and DSTL Sensors Department reinforced the opinion that insufficient data was available to predict the impact of increasing the depth of a wind turbine farm relative to the radar. **It is recommended that a further study be conducted in order to determine the impact of an extended radial deployment of wind turbines relative to an AD radar.**

19. Clutter. Theoretical studies into the impact of wind turbines on AD radar had been predicated on the assumption that clutter induced by the turbines would be a major factor. During this Trial, only relatively small amounts of clutter were displayed to the operator; approximately 5-10 unwanted primary returns per sweep were displayed when all 103 turbines were rotating at their standard rotational rate. Further, the amount of clutter did not increase even when the wind direction was such that all the turbines were rotating in a direction perpendicular to the radar beam, maximising the Doppler effect. Based on the combination of T101 and wind turbine farms used for this Trial, there was no significant operational impact from displayed clutter resulting from wind turbine farms in line of sight of AD radars. However, the variables that impact on levels of displayed clutter include: radar type, turbine parameters, location and weather. Thus, this observation should not be automatically read across to other radar types or wind turbine farm installations. Moreover, it is likely that proliferation of wind turbine farm developments within LoS of a single radar head would significantly increase the clutter problem. An increase in displayed clutter is also likely if the overall RCS of an individual wind turbine farm is increased, as a result of either larger turbine installations or greater numbers of turbines within a given development. **It is recommended that further studies be conducted in order to determine the levels of wind farm induced clutter displayed on other in-service AD radars.**

20. Tracking Anomalies. AD Radars in the UK are not used in isolation. The data from a number of static radar sites (Type 91, Type 92 and Type 93 military radars augmented by NATS radar data) is fed into the UCCS in order to support both the production of a Recognized Air Picture and provision of ATS. This data is imported in a format known as SLR/SDO/1000/1 Issue 2, a standard protocol that carries radar plot data but no derived track information. A Saab Multi- Sensor Tracker (MST) integrated within UCCS forms the tracks that are displayed to operators. Moreover, any tracker, be it within UCCS or an integral part of an individual radar, will always use all available data when compiling and maintaining a track picture. There are 3 distinct tracking anomalies that could occur as a result of interference from a wind turbine farm:

- a. Track Seduction. Track seduction occurs when a valid track is caused to alter its direction based on false plot information. Seduction occurred during Stage 1 of the Trial when no corresponding SSR data was available for the participating aircraft. During Stage 2, with SSR data available, seduction was not observed.

b. False tracks. False tracks are produced as a result of displayed clutter that behaves in a manner consistent with plot data derived from a true target. The extent to which a tracker will suffer from false track initiation is dependent on the sophistication of the individual tracking system. Numerous false tracks were produced by the T101's integral tracking system during the Trial but an experienced T101 operator quickly cancelled these. It is important to note that not all AD radars are manned by radar operators. A fully automatic tracker may not necessarily be relied on to cancel false tracks consistently. AD radar tracks are not passed to UCCS and no data was gathered to assess the vulnerability of the Saab MST to false track initiation due to clutter induced by a wind turbine farm.

c. Failure to Track. As long as a tracker is receiving valid SSR returns from a target aircraft then its ability to track will not be compromised by the presence of a wind turbine farm. During Stage 2 of the Trial, all participating aircraft were squawking Mode 3(A)/C SSR at all times; therefore, tracks were initiated and maintained on these aircraft throughout this Stage of the Trial. However, the T101 did not interrogate SSR during Stage 1 of the Trial and significant degradation of tracking performance was observed. Where a target aircraft does not squawk SSR it is highly likely that the associated track would drift when the aircraft overflies a wind turbine farm or flies through the shadow area. Provided that the aircraft does not manoeuvre and the track is not seduced then the system should resume tracking as soon as primary radar returns are available. Otherwise, a new track is likely to be initiated at this point.

It is recommended that a further Trial be conducted to ascertain the vulnerability of the Saab MST to clutter resulting from the presence of a wind turbine farm in line of sight of an AD radar.

21. Three-Dimensional (3-D) Accuracy. A key feature of AD radars is their ability to determine the height of an aircraft that is not transponding SSR Mode 'C'. Height information derived solely from the primary radar returns is generally assumed by AD operators to be within 5000 ft of the actual aircraft height. However, during Stage 2, height data derived from primary radar returns was observed to fluctuate considerably from the norm. Errors of up to 10 000 ft were observed throughout the trial stage when aircraft were directly overhead the wind turbine farm. This problem is believed to be attributable to the techniques used by the T101 to calculate heights and may not be applicable to other AD radars.

22. SSR. It was not anticipated that a wind turbine farm would interfere with SSR performance and no effect was observed during this Trial.

TRIAL OBJECTIVES SATISFIED

OBJECTIVE 1. DETERMINE THE ADVERSE EFFECTS OF WIND TURBINE FARMS ON RADAR PERFORMANCE

23. The determination of the adverse effects of wind turbine farms on radar performance addressed 3 areas:

- a. Probability of Detection. The constraints on trial design imposed by selection of a suitable radar deployment site within line of sight of a suitable wind turbine farm precluded the conduct of a long-range Probability of Detection sortie during this Trial.
- b. Tracking. Tracking effects were assessed during the Trial, but only in terms of the impact on the T101's own tracker. All the participants in Stage 2 were tracked using their SSR transponder return even when the wind turbines masked primary radar returns. The effect of wind turbines on the performance of the Saab MST within UCCS was not assessed.
- c. Displayed Effect. The extracted plot data as displayed on the operators screen within the T101 cabin is identical to the data that is transmitted to UCCS for display to operators in the wider ASACS community. The displayed effect, clutter, resulting from the presence of a wind turbine farm was assessed from the T101's integral display system and the results can be regarded as valid for any standard system displaying the same data. OBJECTIVE PARTIALLY SATISFIED

OBJECTIVE 2. PROVIDE A PREDICTION ON THE EFFECTS OF LOW-LEVEL COVERAGE DUE TO THE WIND TURBINE FARM

24. The low-level sortie profiles used during this Trial were designed to place aircraft on the radar horizon directly behind the wind turbines. However, once the aircraft were clear of the shadow area discussed at paragraph 19 there was no discernible impact on low-level coverage. OBJECTIVE FULLY SATISFIED

OBJECTIVE 3. PROVIDE GUIDANCE ON SYSTEM SET-UP AND OBSERVED DISPLAYED EFFECTS

25. System set-up is specific to individual radar types and the T101 is not part of the normal UK backbone radar chain. However, different modes of operation for the T101 were employed during the Trial, particularly with regard to the operation of the MTI circuitry. Changes to the standard set-up and operation of the T101 did not improve its performance in the vicinity of the wind turbines. Moreover, the displayed effects were specific to the T101 in this configuration and difficult to read across to other radar types or wind turbine farm locations. Notwithstanding the above, the displayed effects were not operationally significant. OBJECTIVE FULLY SATISFIED

ADDITIONAL OBSERVATIONS

26. Having observed the operationally significant problem of overhead obscuration during this Trial, it is impossible to recommend any changes to system set-up or operating procedures in order to mitigate this problem. However, technical solutions have been considered, in consultation with AMS and DSTL. These are explained in depth at Annex F.

CONCLUSIONS

27. At the outset of the Trial, it had been assumed that displayed clutter in the vicinity of a wind turbine and low-level shadowing behind the turbine would be the most significant adverse operational effects on AD radar in proximity to wind turbines. Both were observed during the Trial but displayed clutter was minimal and the shadow region was bounded to a depth of only a few kms. Observations during Stage 1 of the Trial suggested significant obscuration of primary radar returns overhead wind turbines and this was borne out through deliberate sortie design during Stage 2. This effect was observed independently of the height of the aircraft, throughout the full height range used for the Trial (2000 ft-24 000 ft above mean sea level) and is now believed to represent the most significant operational effect of wind turbine farms on AD operations. Alternative configuration of AD radars or changes to standard operating procedures do not offer a solution to this problem. Technical solutions are possible but further work, both theoretical study and practical trials, are necessary to confirm the feasibility of the proposed solutions. Overall, the Trial established that there is a significant operational impact of wind turbines in line of sight of AD radars. This effect was independent of radar to turbine range and aircraft height. Where a target aircraft does not squawk SSR it is highly likely that the associated track would drift when the aircraft overflies a wind turbine farm or flies through the shadow area. Provided that the aircraft does not manoeuvre and the track is not seduced then the system should resume tracking as soon as primary radar returns are available. The existing MoD guideline safe-range for wind turbine farms of 74 km from AD radar when in line of sight was deemed to be irrelevant. Line of sight was assessed to be the only relevant criterion when considering objections to wind turbine farm developments.

RECOMMENDATIONS

MAJOR RECOMMENDATIONS

28. It is recommended that:
- a. Automatic approval of wind turbine farms based on ranges beyond 74 km ceases.(Para 16a)
 - b. The potential impact of any wind turbine farm within radar line of sight of an AD radar, regardless of range, be closely examined. (Para 16b)

- c. Personnel using AD radars in support of the provision of ATS be informed that they are likely to lose primary radar returns over wind turbine farms and should consider limiting the radar services they offer accordingly. (Para 16c)
- d. Accurate positional data for UK wind turbine farms is made available to personnel using AD radars to support the provision of ATS. (Para 16d)
- e. The cumulative impact of wind turbine farm developments be considered with regard to limiting the number and size of shadow regions in close proximity to each other. (Para 17)
- f. A further study be conducted in order to determine the impact of an extended radial deployment of wind turbines relative to an AD radar. (Para 18)
- g. Further studies be conducted in order to determine the levels of wind farm produced clutter displayed on other in service AD radars. (Para 19)
- h. A further Trial be conducted to ascertain the vulnerability of the Saab MST to clutter resulting from the presence of a wind turbine farm in line of sight of an AD radar. (Para 20)

<Original signed>

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6 Jan 05

Annexes:

- A. [Windfarm Data During Trial Stage 2.](#)
- B. [Sortie Profiles – Stage 2.](#)
- C. [RADAC Output.](#)
- D. [Proposed Explanation for Overhead Obscuration.](#)
- E. [Mitigation Of Shadow Region Behind Wind Turbine Farms.](#)
- F. [Possible Technical Solutions to Overhead Obscuration.](#)

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WINDFARM DATA DURING STAGE 2

1. Data was collected on activity levels for the wind turbine farm during Stage 2 of the Trial. The key data was as follows:

Date	Time (local)	Turbines Operating	Wind Direction	Wind Speed (ms⁻¹)	Weather
15 Sep 04	08:45	15	N/K	5.4	clear
	09:55	46	WSW	6.1	clear
	11:15	92	WSW	6.7	clear
	12:08	102	WSW	7.5	clear
	14:20	102	SW	6.6	clear
16 Sep 04	09:50	102	S	10.5	cloudy
	11:15	103	SSE	11	cloudy
	13:07	103	SSE	12.1	cloudy

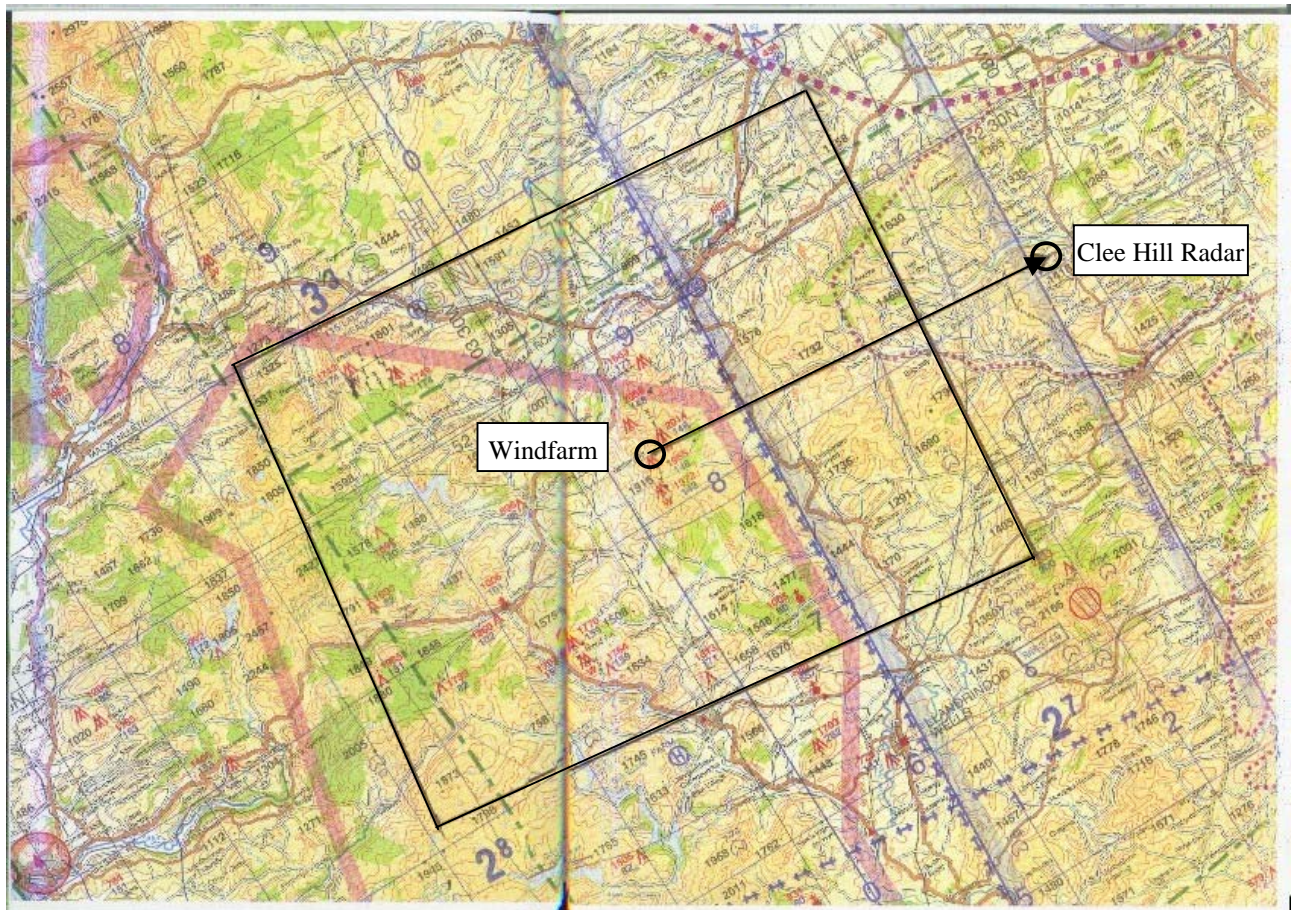
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SORTIE PROFILES – STAGE 2

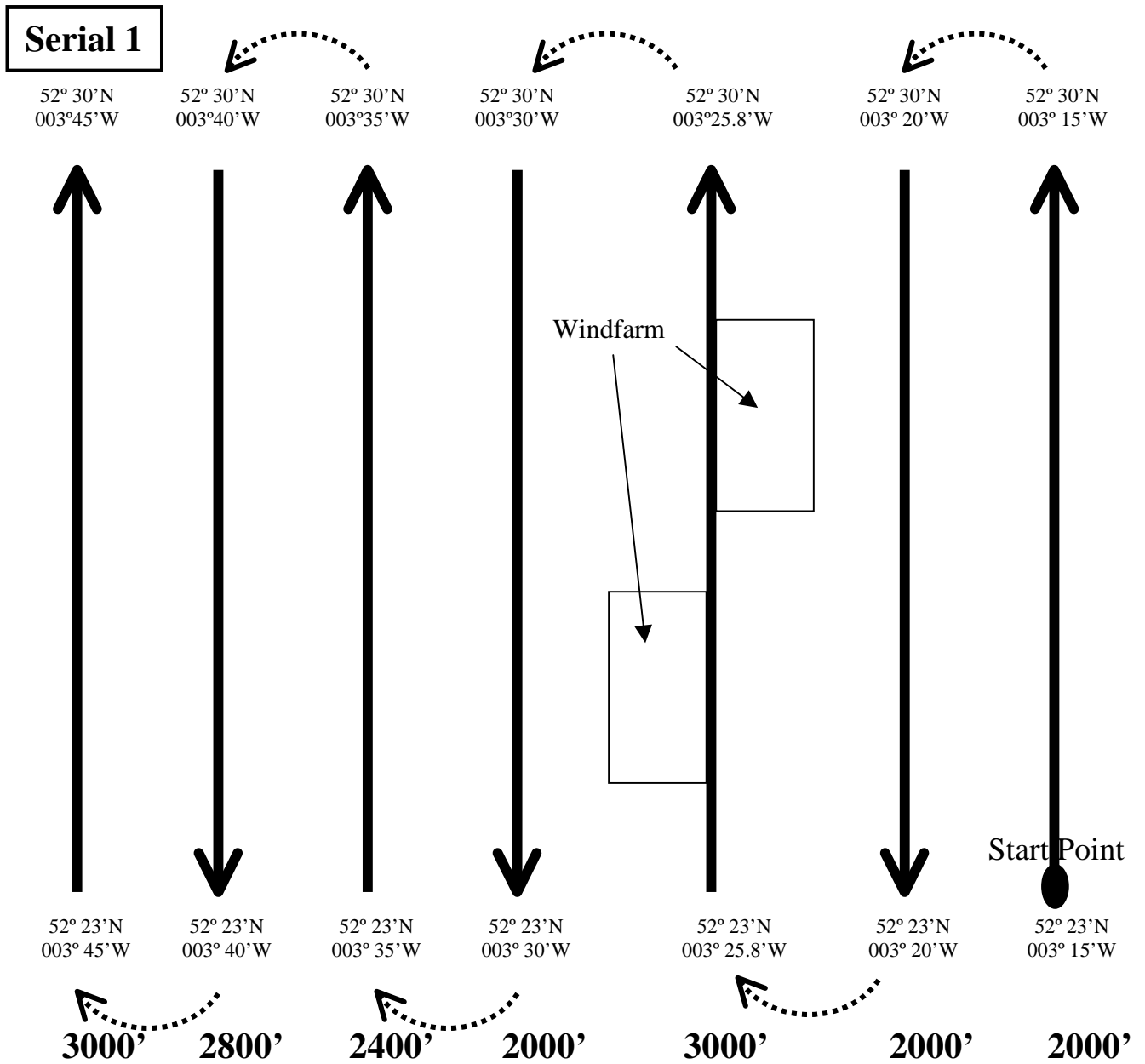
1. The profiles were a tangential and radial route, repeated at various heights. The Trial area is shown below:



2. The following sorties were tasked in support of the Trial - Stage 2:

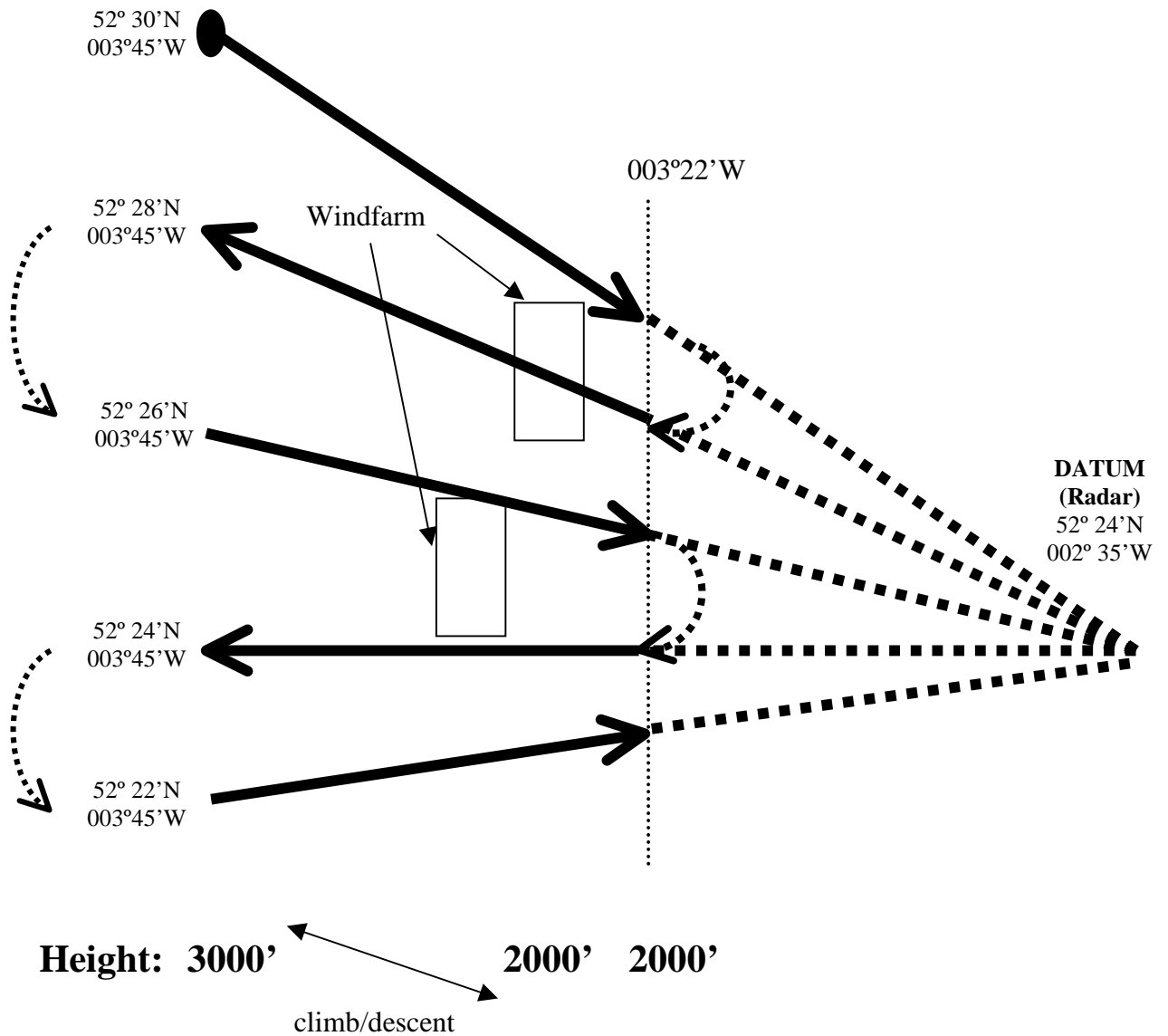
- a. King Air. Time on Task (TOT) 150830Z to 151130Z.
- b. Chinook HC Mk 1. TOT 151130Z-151230Z and 151430Z-151630Z.
- c. Hawk T Mk 1. TOT 151300Z to 151400Z reserve 161300-161400Z.
- d. Tucano. TOT 161130Z to 161300Z.
- e. Dominie. TOT 160900Z to 161000Z.

3. Profiles. The co-ordinates for the trial profiles are shown in the following diagrams:



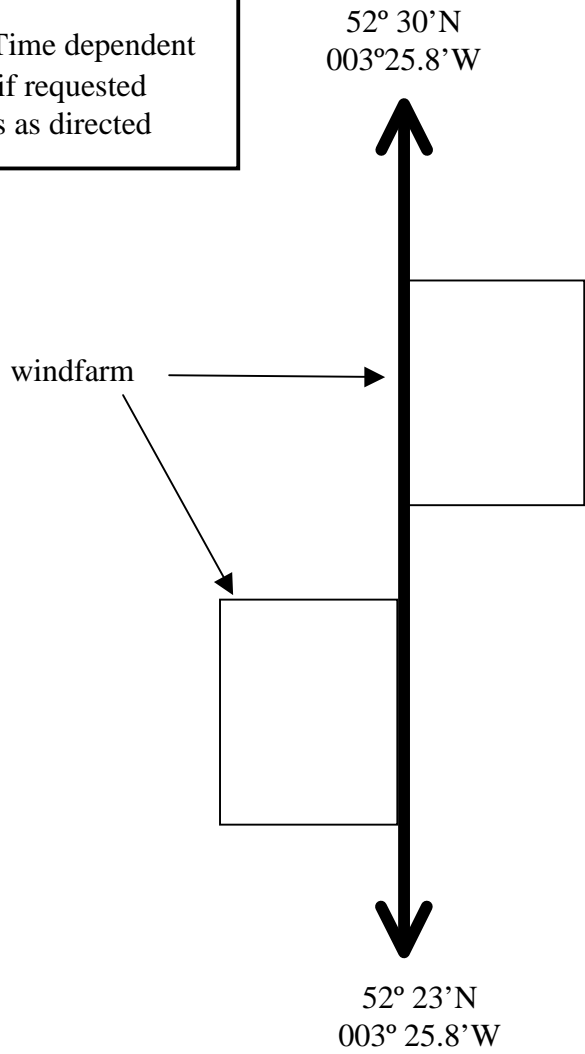
All Heights: - AMSL, minimum desired height
(Pilot to use higher as required for safety of flight)
- Climb only in turn

Serial 2



All Heights: AMSL, minimum desired height
(Pilot to use higher as required for safety of flight)

Serial 3 – Fuel / Time dependent
– Flown if requested
– Heights as directed



All Heights: - AMSL, minimum desired height (higher as required for safety of flight)
- climb only in turn

RADAC OUTPUT

1. Analysis of the radar plot data as captured by DEI&IS using RADAC clearly shows the loss of primary data for some aircraft overhead the wind turbines. The complete output of the RADAC from the Trial will be analysed in full by DEI&IS and presented by them in a separate report. An example of the overhead obscuration that was observed during the Trial, is shown at Figure 1; the T101 clearly loses primary responses from a Hawk T Mk1 travelling north over the turbines at 10 000 ft. For clarity, an oval has been overlaid to indicate those plots where only an SSR response was obtained.

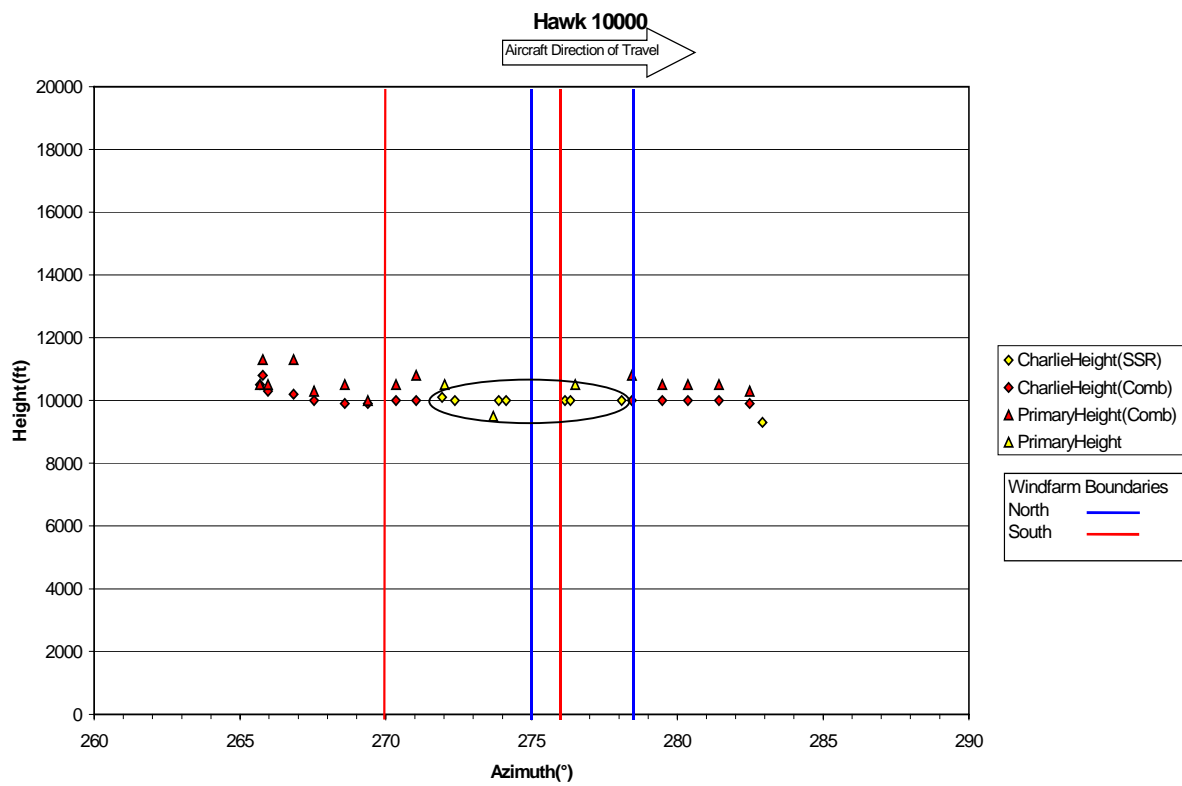


Figure 1 - Hawk Northbound over Turbines (10 000 ft)

2. By contrast to the data at Figure 1, obtained from the Hawk T Mk 1A aircraft sortie, data from the Dominie T Mk 1A ac sortie is shown at Figure 2, below. The radar returns for the Dominie T Mk 1A ac at this height were consistently combined (primary and SSR) throughout the assessed profile.

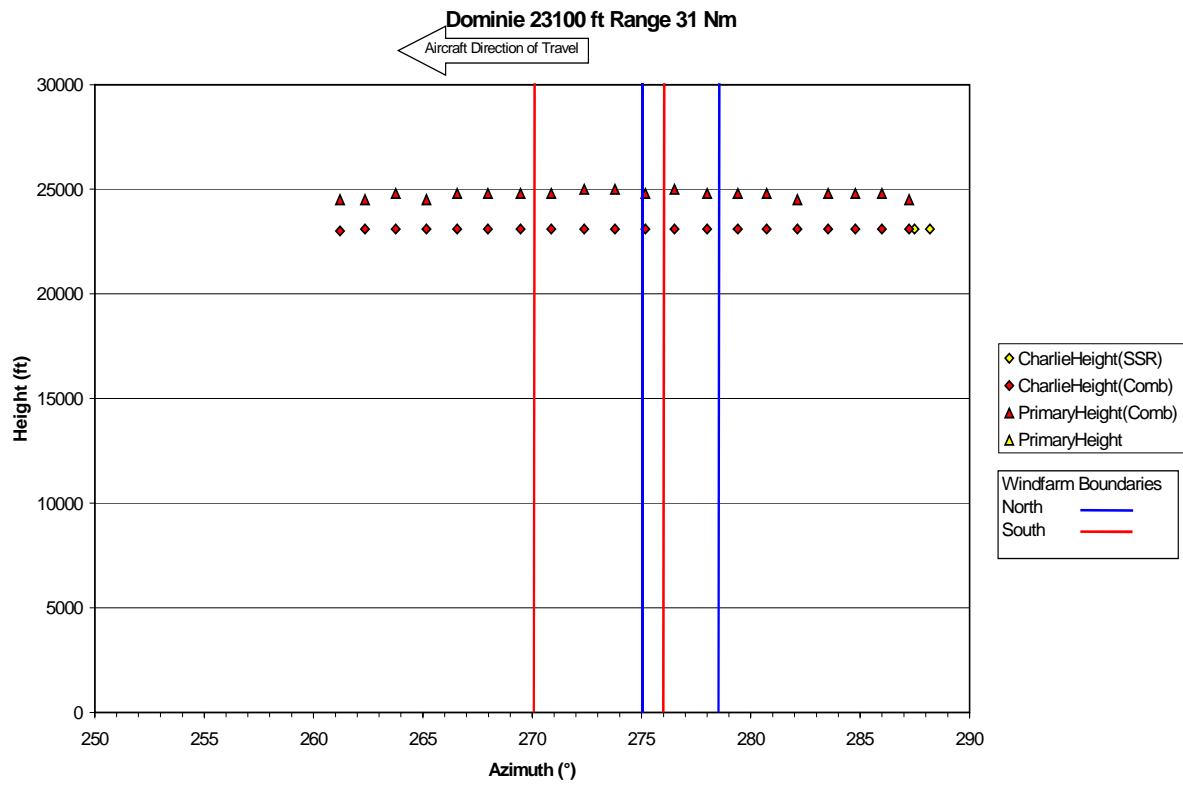


Figure 2 – Dominie Southbound over Turbines (23 100 ft)

3. Examining the plot data captured over time, shown at Figure 3, allows the shadow effect to be more clearly seen. The rectangular areas overlaid on the graph approximate those areas within which there is a significantly increased incidence of dropped primary returns. Further study would be necessary in order to determine both the exact bounds of this shadow area and its dependencies.

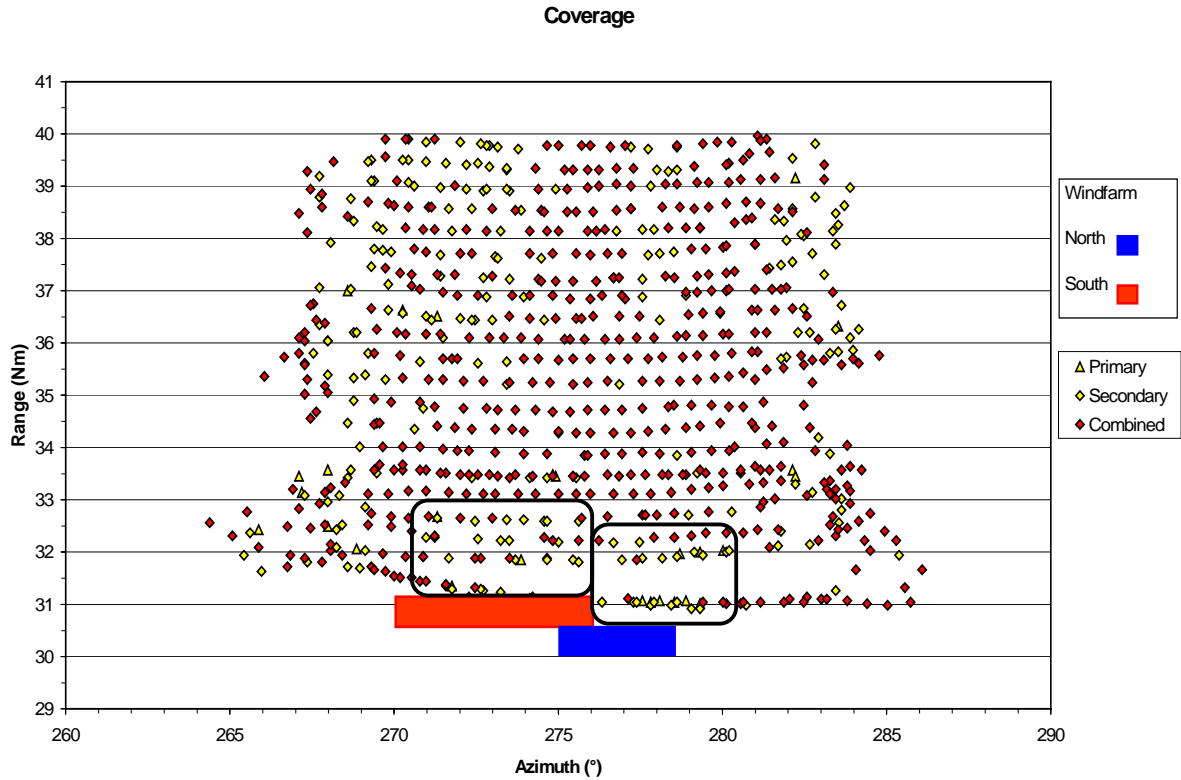


Figure 3 - Composite Plot Data during The Trial

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PROPOSED EXPLANATIONS FOR OVERHEAD OBSCURATION¹

CLUTTER THRESHOLDS BASED ON ELEVATION SIDELobe ENERGY

1. The hypothesis regarding the overhead obscuration effect observed during this Trial is that it was a result of a signal being received in the elevation side-lobes of the upper beams. Empirical evidence collected during the Trial suggested that only aircraft with a very small RCS were subject to this overhead obscuration effect. Both the Tucano T Mk 1 and the Hawk T Mk 1A aircraft, with RCS of approximately 1m^2 were obscured but the Dominie T Mk 1A aircraft, with RCS of approximately 10m^2 was not.
2. For the T101, the elevation main-lobe is approximately 25 dB up on the elevation side-lobe. The RCS of the turbines used during the Trial was not assessed directly. However, other studies suggest that wind turbine masts have an RCS of $30\text{-}60\text{ dBm}^2$, a $30\text{-}60\text{ dB}$ gain over the Hawk T Mk 1A and Tucano T Mk 1 aircraft. The automatic clutter maps for the T101 are set based on large range-cells (considerably larger than the radar resolution range cell) in either ground (beam 1), or aloft (beams 2-7). Figure 4 is a representation of the T101 beam pattern. Therefore, it is likely that the aloft clutter map overhead the wind turbines would be set based on returns received from the turbines through the elevation side-lobes. For aircraft with an RCS between 30 dB and 60 dB down on that of the turbines, this appeared to result in rejection of the aircraft return. It is believed that this effect is independent of radar to turbine range.

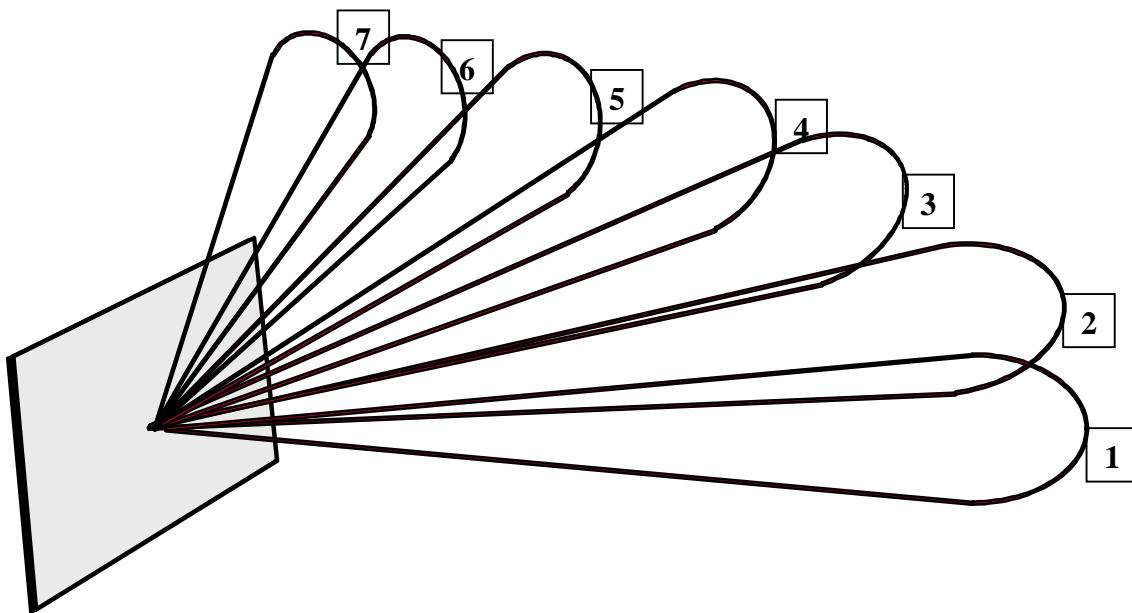


Figure 4 - Vertical Beam Stacking in the Type 101 Radar

¹ Representing the opinion of the Air C2 OEU but supported by discussion with DSTL and AMS.

3. A more detailed study would be necessary in order to determine the validity of this hypothesis. In particular, the exact sensitivity of elevation sidelobes in both transmit and receive would have to be considered and the elevation angle between the antenna and the wind turbines calculated. However, this hypothesis was originally suggested by a representative of DSTL and represents the current combined opinion of those AWC and DSTL staff participating in this Trial.

AMTI AND DOPPLER NOTCH

4. The T101 employs Adaptive Moving Target Indication (AMTI) techniques. The AMTI processing assesses the background Doppler returns being received in each of its range cells and sets a velocity for which returns are 'notched out'. The tip speed of the turbines at the P&L wind farm during the Trial was of the order of 100 ms^{-1} (approximately 200 kts). It is possible that aircraft detected in the same AMTI range cell as a rotating turbine may fall into the AMTI Doppler notch and be discarded. All aircraft participating in this Trial maintained a ground speed of approximately 200 kts or less. It is, therefore, possible that some returns may have been lost due to the presence of an AMTI Doppler notch. However, this is unlikely to have been the cause of the observed obscuration for the following reasons:

- a. The vast majority of the sorties during which overhead obscuration was observed at high level were flown in accordance with Serial 3, as detailed at Annex A. This serial places the aircraft at an almost perfect tangent to the radar beam, thus giving near zero Doppler shift.
- b. The Hawk T Mk 1A and Tucano T Mk 1 aircraft were obscured when over-flying the wind turbines but the Dominie T Mk 1A aircraft was not, despite flying the same profile at a very similar ground speed. The only significant difference was ac type (and thus RCS) not ac velocity, making clutter suppression due to elevation sidelobe sensitivity a more likely explanation than AMTI Doppler notch. However, the velocity of the 3 aircraft types was not identical and so the impact of an AMTI Doppler notch cannot be ruled out without further investigation.

Overall, we do not believe a Doppler notch resulting from AMTI processing to be the likely cause of overhead obscuration but it is impossible to rule it out completely based on the information available at this time.

WEATHER CLUTTER

5. It has been suggested by DEI&IS that the overhead obscuration may have been the result of the impact of weather clutter over the ridge on which the wind turbines were located. The majority of the Trial was conducted with light cloud cover in low level layers over the turbine farm. There is no body of evidence available to state exactly how a T101 radar would process returns in the weather clutter experienced during the Trial. Therefore, there is insufficient evidence to rule out this possible explanation.

MITIGATION OF SHADOW REGION BEHIND WIND TURBINE FARMS

1. Dimensions of Shadow Region. The shadow region behind a wind turbine farm within which primary radar contact is masked by interference with the propagation of the radar beam is believed to be defined by a straightforward geometric relationship between the radar and the wind turbine farm, as indicated below:

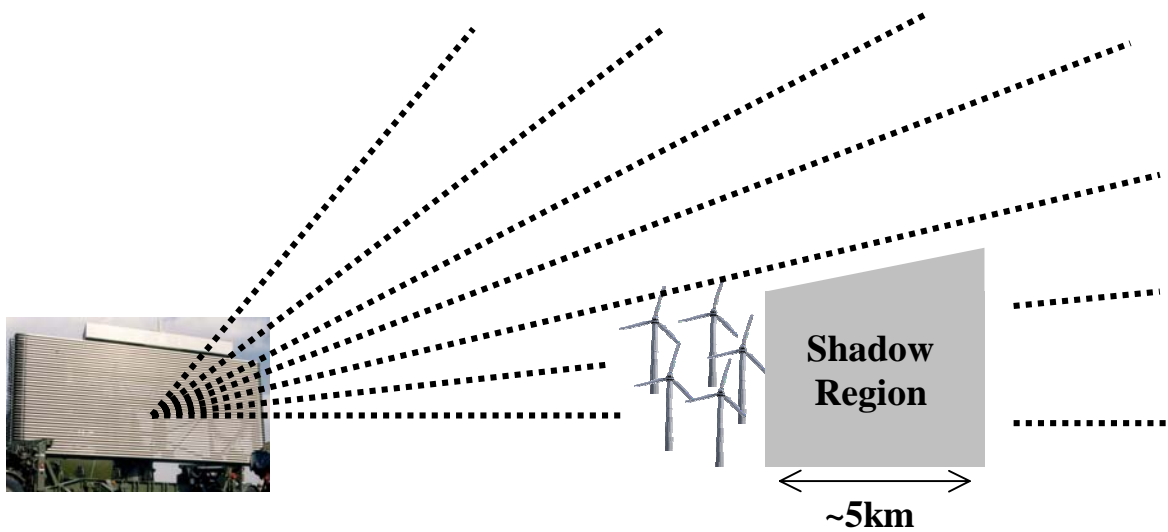


Figure 5 - Shadow Region behind Wind Turbine Farm

If we consider the extreme case where the entire vertical coverage of an individual radar beam (qv Annex D, Figure 4) is obscured when any part of that beam has direct LoS to the wind turbines (in radar beam main lobe) then we can easily calculate the vertical extent of the shadow. The centre of beam one, the lowest beam on the T101, is at an elevation of approximately 0.5° and the centre of beam 2 is at approximately 2° , beam width for both is less than 3° . Therefore, at 35 nm (the radar to turbine range observed during Stage 2 of this Trial) the top of beam one is at approximately 2000 ft and the top of beam 2 is at approximately 8000 ft. Definition of the lateral bounds, including depth, of the shadow region is less simple. Shadowing has thus far been observed to occur only to a depth of approximately 5 km, when assessed using a wind turbine farm approximately 5-7 turbines deep. It is not known whether a deeper deployment of turbines relative to the radar head would significantly effect the propagation of the radar beam.

2. Overlapping Radar Cover. In those instances where more than one AD radar, or alternative radar source available to ASACS, have LoS to the same wind turbine farm from different directions there will be a reduction in the composite shadow region resulting from a combination of their data. Provided 2 radars are greater than 90° apart in terms of radials from the wind turbine there should be no composite shadow region, the effect would have been fully mitigated. However, the overhead obscuration would always remain.

3. Size and Location of Wind Turbine Farms. When considering applications for wind turbine developments it is necessary to assume that an approximately semi-circular shadow

region will exist behind the development relative to any radar with line of sight. The lateral bounds of the shadow are directly related to the size of the development; the factors determining the depth of the shadow are unknown. It is expected that small, low density developments would have a proportionally lesser impact. The operational impact of these shadow regions can only be assessed on a case by case basis and with due heed to the cumulative effect of large numbers of turbines or multiple farms in close proximity.

4. Detection Outside Shadow. Conventional AD operations would allow for detection of threat aircraft at ranges well beyond the relatively limited shadow region behind a wind turbine farm. In these specific instances, the effect would be mitigated by early detection. However, the events of 9/11 in the USA have highlighted the significant potential for a threat to emerge overland. It is therefore possible to use long-range detection as a mitigation for the shadow region only in certain scenarios.

POSSIBLE TECHNICAL SOLUTIONS TO OVERHEAD OBSCURATION²

1. Existing AD Radar. It appears that the overhead obscuration that was observed during the Trial was dependent on how the ratio of wind turbine farm RCS to tgt RCS (currently approximately 30-60 dB for aircraft with 1m² RCS) compares with the ratio of main lobe to sidelobe sensitivity (20-25 dB for the T101 receive beam). The strong returns from the wind turbines appear to be influencing the clutter maps produced by the T101 processing system; further studies are required to prove this theory. Possible solutions to this problem based on existing AD radars take several forms, as follows:

- a. Tgt RCS. Increasing the RCS of the tgt aircraft would increase the probability of detection against a high noise threshold, such as that found over a wind turbine farm. However, we have no control over the RCS of a tgt aircraft and no reason to believe that our current benchmark of 1 m² is unrealistic. Therefore, this is not a valid solution to the problem.
- b. Radar Sidelobe Sensitivity. Advice received from DSTL suggests that the likely best performance of an elevation sidelobe in the receive beam of a current generation long range AD radar is a 30 dB reduction compared to the main lobe. Greater than 30 dB reduction in sidelobe sensitivity relative to the main lobe is expected to result in significant reduction of main lobe sensitivity. Given that the primary purpose of AD radars is long-range surveillance, any significant loss of main lobe sensitivity would be unacceptable. Therefore, reduced sidelobe sensitivity is not expected to offer a valid solution to the problem.
- c. Turbine Installation RCS. Decreasing the RCS of the wind turbine installation would have a complementary effect to reducing tgt RCS. The net result would be to reduce the strength of the primary radar energy reflected into the elevation sidelobe and thus reduce the overall noise floor used by the clutter suppression circuitry of the radar. A reduction in the turbines RCS to approximately 20 dBm² would likely be sufficient to allow a 1 m² tgt to be detected. This represents a valid solution to the problem of overhead obscuration. However, reduction of the RCS of a large wind turbine farm would be technically complex.
- d. Alternative Processing Methodology. The processing applied by the T101 used for this Trial allows beams 2-7 to exert equal influence on the 'aloft clutter map' (as distinct from the 'ground clutter map' based solely on beam 1). This clutter map is then used to determine the sensitivity thresholds for the various beams of the radar. It is likely that the first elevation side-lobe of beam 6 or beam 7 is the major contributing side-lobe return. However, the subsequent clutter map would still reduce the effective sensitivity of beams 2-7. Altering the way in which the clutter map thresholds are handled within the radar offers a significant potential for improvement. The scope for alterations to existing radar will necessarily be limited by legacy hardware and is likely to incur significant costs. The observations of this Trial could be used to inform the design of processing

² Representing the opinions of the Air C2 OEU but based partly on discussions with AMS and DSTL.

algorithms in future radar projects, particularly with regard to how the upper beams form their clutter maps and set their thresholds.

The solutions detailed above are predicated on the assumption that the overhead obscuration is a direct result of raised noise thresholds in the clutter suppression circuitry resulting from reflected energy detected in the elevation sidelobes. A full scientific analysis of what information the radar processor is receiving and how it is dealing with it would be necessary in order to support this theory. This analysis would require the employment of additional equipment attached to the various stages of the radar processing chain during another live flight trial.

2. Existing Alternative Ground Radars. Non-AD radars are already available to UK ASACS(both long-range search radars belonging to NATS and short-range RAF airfield radars (Watchman). These radars are 2-dimensional and employ different technological solutions to provide their plot information. At this stage it is anticipated that 2-dimensional radars will suffer a greater degree of overhead obscuration as the wind turbine farm will always be in the elevation main lobe; this is in contrast to the problems already observed with 3-dimensional AD radars when the wind turbines were in the elevation sidelobe, a considerably less sensitive (20-25 dB) part of the beam. A study into these radars' susceptibility to interference from wind turbines is already planned; this Trial will take place in Nov-Dec 04. There is currently no evidence to suggest that a fused picture of existing sensors offers a solution to the overhead obscuration problem observed during the AD radar Trial. However, a sufficiently comprehensive fused picture may address the issue of shadowing.

3. Alternative Technologies. Aside from modifications to existing systems, there are technological solutions that are worthy of consideration, these include:

a. Active Phased Array Radar. The Sampson Radar to be fitted on the RN's new Type 45 Destroyers uses active phased array transmitter technology. Active phased array antennas allow considerably enhanced control over beam forming and steering; control of sidelobes is therefore far more flexible than with existing passive phased array systems. Moreover, many active phase array radars already support the steering of nulls in the receive beam as an Electronic Protection Measure to counter jamming. Steering of nulls in the transmit beam is less common but is technologically feasible, particularly for static radar installations such as those employed by UK ASACS. However, current generation active phased array radars represent an expensive, and unproven, solution to this problem. Whilst active array technology should certainly be considered under future sensor procurement programmes it unlikely to offer a short term solution to the problems observed during this Trial.

b. Predictive and Multi-Sensor Trackers. There have been proposals to employ specialist tracking systems to overcome the impact of wind turbine farms on radar, most notable amongst these is the Advanced Digital Tracker (ADT) being offered by AMS, manufacturer of the T101 and T93 AD radars. The ADT offers the addition of plot extraction and tracking to any compatible radar, including the Watchman already in service with the RAF. However, AD radars already employ both plot extraction and advanced predictive tracking algorithms. The applicability of the ADT to AD radars is therefore questionable. Moreover, only the plot output from AD radars is transmitted to UCCS for use in compiling the Recognized Air Picture; SLR/SDO/1000/1, the format used between radars and UCCS is incapable of transmitting track data. UCCS already

incorporates an advanced multi-sensor predictive tracker. Finally, the most significant operational impact of wind turbine farms on AD radars was not assessed to be clutter or tracking anomalies. Overhead obscuration, followed by shadowing, were the most significant effects. The ADT does not address either issue. However, the ADT does offer some potential for the radar processing system to make a semi-intelligent assessment of returns from the vicinity of a wind turbine farm in order to distinguish clutter, including that induced by turbines, from aircraft. If such a system proved to be sufficiently robust then thresholds could be lowered and detection of aircraft over turbines improved. Further investigation of this option is required before a final recommendation can be made.

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