FURTHER EVIDENCE OF THE EFFECTS OF WIND TURBINE FARMS ON AD RADAR

12 AUG 05

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TRIAL REPORT

FURTHER EVIDENCE OF THE EFFECTS OF WIND TURBINE FARMS ON AD RADAR

EXECUTIVE SUMMARY

1. The Government is supporting the introduction of wind turbine farms within the UK as part of its renewable energy strategy. As a result of the Government's policy, there has been a rapid increase in the number of planning applications for wind turbine farms, including offshore developments. Prior to conducting live flight trials in 2004, the MoD scrutinised planning applications for wind turbine farm developments within 74 km and Line of Sight (LoS) of a primary Air Defence (AD) surveillance radar. However, following those trials, the resultant Trial Report recommended that the MoD scrutinise wind turbine farm planning applications within LoS of AD radars, regardless of range. As a result of this recommendation, the MoD temporarily removed the 74 km range limit. There remains a requirement for MoD to provide more robust and substantiated evidence in support of this policy change. Consequently, the Directorate of Counter Terrorism and United Kingdom Operations (D CT&UK Ops) tasked the Air Warfare Centre (AWC) (Air Command and Control Operational Evaluation Unit (Air C2 OEU)) with gathering further evidence on the effects of wind turbines on AD radar performance. This task was conducted as a live flight trial during the period 29 Mar – 8 Apr 05.

2. Sorties in support of this trial utilised Hawk T Mk1A, Tucano T Mk1 and Dominie T Mk1A ac to ensure that a range of ac Radar Cross Sections (RCS) was considered. All relevant permutations of significant radar set-up parameters were tested during the trial to ensure that a complete data set was obtained.

3. The results of this trial supported the theories formed as a result of previous trials and validated the recommendations made therein. The presence of a hole in detection at all levels overhead a wind turbine farm was shown to result from the presence of a large radar reflector (the wind turbines) in direct LoS of the radar antenna. The use of a coarse Clutter Map together with sharing of Clutter Maps between multiple beams significantly exacerbated the problem. Other clutter suppression circuitry, in this case the Background Averager, was also shown to have an effect. Where a radar beam was free of reflections from the wind turbines then it could detect and track even a low RCS ac such as the Hawk T Mk1A directly above the turbines. Whilst the results of this trial were focused on the T101 Radar, they established several key principles that can be applied when considering the vulnerability of any radar system to interference from wind turbines. Most significantly, the value of independent clutter processing in all beams of a 3-D radar, coupled with a fine resolution Clutter Map, was demonstrated.

TRIAL REPORT

FURTHER EVIDENCE OF THE EFFECTS OF WIND TURBINE FARMS ON AD RADAR

INTRODUCTION

4. The Government is supporting the introduction of wind turbine farms within the UK as part of its renewable energy strategy. As a result of the Government's policy, there has been a rapid increase in the number of planning applications for wind turbine farms, including offshore developments. Prior to conducting live flight trials in 2004, the MoD scrutinised planning applications for wind turbine farm developments within 74km and LoS of a primary AD surveillance radar. The first trial report recommended that the MoD scrutinise wind turbine farm planning applications within LoS of AD radars, regardless of range. As a result of this recommendation, the MoD temporarily removed the 74 km range limit. There remains a requirement for MoD to provide more robust and substantiated evidence in support of this policy change. Consequently, D CT&UK Ops tasked the AWC (Air C2 OEU) with gathering further evidence on the effects of wind turbines on AD radar performance. This task was conducted as a live flight trial during the period 29 Mar – 8 Apr 05.

AIM

5. The aim of this trial was to generate evidence to inform the MoD's policy on wind turbine farm developments in LoS of AD radars.

TRIAL OBJECTIVES

6. The objectives of this trial were to:

a. Record unprocessed, pulse-to-pulse video phase history data from an AD radar in its different modes of operation, against a variety of ac in the vicinity of wind turbines.

b. Compare Ac and Windfarm Digital Scan Converter output for each receiver beam of the Type 101 (T101) Radar under all relevant permutations of processing and filtering techniques employed by the system.

c. Provide guidance on mitigation of the interference effects between wind turbines and AD radars.

d. Record radar data in a form in which it may subsequently be replayed for detailed analysis.

CONDUCT OF TRIAL

GENERAL OUTLINE

7. Wind farms are currently precluded from being located in close proximity to UK Static AD Radars and this severely restricted the choice of location for the Trial. It was necessary to use a deployable AD Radar at a location in LoS of a suitable wind farm. The only deployable AD Radar in the UK inventory is the T101. The radar was deployed to Clee Hill[1], Shropshire, in LoS of the P&L[2] Wind Farm south west of Newtown in Powys, Wales, during the period 29 Mar – 8 Apr 05. A range of fixed-wing air platforms was tasked to perform planned sortie profiles overhead and in the vicinity of the wind turbine farm. Sortie flight profiles are at Annex A.

8. To satisfy the objectives of the Trial, operating and technical data was gathered from the T101 radar for later playback and analysis. Data recording was conducted by the Defence Communication Services Agency (DCSA) Directorate of Chief Technical Officer (DCTO)[3] and Protab Ltd. Additional recordings were made manually using conventional video camcorders. The radar returns were recorded at different points within the processing architecture of the radar to provide a quantitative measurement of the performance of the T101 radar for subsequent analysis. BAE Systems (BAES) Insyte also gathered processor-level performance data during the Trial for internal analysis; their activity was dependent on this Trial but did not impinge upon the successful completion of the Trial.

EQUIPMENT UNDER TEST

9. The equipment under test was the T101 Radar, although the results of the Trial were intended to inform MoD policy relating to all AD radars. The wind turbine farm under test was the P&L Wind Farm, commissioned in Jan 1993 and comprising 103 Mitsubishi Type 300 turbines. The radar to wind turbine farm range was 57 km.

TRIAL METHOD

10. Trial Sorties. This Trial was intended to build upon the success of previous AD Radar trials and provide robust evidence to further inform MoD policy. It was necessary to record radar data covering all relevant permutations of the radar set-up using a variety of ac types, sortie profiles and meteorological conditions. Hawk T Mk1A, Tucano T Mk1 and Dominie T Mk1A ac were tasked to fly sorties in support of the Trial. Sufficient sorties were planned to ensure that all required permutations could be observed. Sortie profiles were designed to allow data to be collected from a combination of radial and tangential flight paths, relative to the radar. As previous trials had indicated obscuration at high levels overhead the wind turbines it was necessary to collect data from surface to 24 000 ft Above Mean Sea Level (AMSL). Further details are at Annex A.

11. Data Capture. To provide a measure of the effects and subsequent evidence of the radar performance, both pulse-to-pulse video phase history and plot data were recorded. DCTO utilised the Radar Data Console (RADAC) and Protab Ltd deployed the Digital Recording Equipment for Analysing Messages (DREAM) system. Both systems captured and subsequently analysed radar plot data. Where possible, ac were fitted with GPS recording equipment to provide accurate positional data. All test equipment was inspected, calibrated and serviceable

[1] In close proximity to the National Air Traffic Services radar site.
[2] P&L Wind Farm is operated by Celt Power Ltd.
[3] Formerly Directorate of Engineering and Interoperability and Information Services.

prior to the commencement of test steps. Accurate local meteorological information was obtained direct from the windfarm operator and is recorded at Annex B.

TRIAL CONSTRAINTS

12. GPS data capture for the Dominie T Mk1A was only partially successful due to an ac equipment failure. Whilst GPS data was desirable to aid post-trial analysis it was not essential and successful analysis of the data captured during this Trial was still possible.

TRIAL RESULTS

TRIAL SORTIES

13. All dedicated trial sorties were lost on the first day, as the T101 was unserviceable. Half of the second day's sorties were lost due to weather. Through a combination of pre-planned reserve sorties and aircrew flexibility in supporting the Trial, all but one of the lost sorties were recovered and sufficient sorties were conducted to ensure that all Trial objectives were completed.

RESULTS

14. General. A key finding of the previous AD Radar Trial was that the effect of wind turbines on radar was predominantly related to the ratio of the RCS of the turbines to the RCS of the target (tgt) ac, with the turbines being considerably larger[4]. This ratio does not change with range from the radar; therefore, it was recommended that the 74 km range limit be removed from the MoD planning guidelines for siting of wind farms in LoS of AD Radars. The data captured during this latest Trial fully supports this previous recommendation. Detailed analysis is at Annex C. **It is recommended that the MoD continues to examine closely the potential impact of any application for a wind turbine farm within radar LoS of an AD radar, regardless of range.**

15. Data Analysis. The data analysis for this Trial broke down into 2 main areas: the impact of wind turbines on a normal radar channel and the impact on a Moving Tgt Indicator (MTI) filtered channel. Within normal radar both the clutter map and Background Averager were considered. For the MTI channel, only the Background Averager was relevant. Finally, the impact of turbines on SSR was considered separately.

16. Normal Radar Channel. Clutter in the normal radar channel of the T101 Radar is filtered by 2 separate processes: the Background Averager and the clutter map. The 2 circuits are effectively independent and were analysed separately:

a. Normal Radar – Clutter Map. The clutter map on the T101 was the subject of considerable focus during and after the previous Trial. The T101 processor overlays a grid of cells that divide the radar's coverage into azimuth sectors and range cells. Due to processing constraints, each clutter map cell is considerably larger than the minimum resolution of the radar. Within each clutter cell the processing threshold is raised or lowered according to the highest single clutter level observed in any one of the radar range cells that it encompasses. If a single wind turbine lies within a clutter cell the processing threshold for the entire cell will be affected. This is explained in more depth

[4] The Mitsubishi Type 300 turbines at P&L are estimated to have an RCS 25dB (315 times) greater than a Hawk T Mk1A.

at Annex D. After the previous Trial, it was postulated that the coarse clutter map was a significant factor in defining the extent of the hole in radar coverage in the vicinity of wind turbines. Analysis of the data captured during this latest Trial strongly supports the theory that when a coarse clutter map is selected to operate over wind turbines, then detection is lost over any clutter cell containing wind turbines. More detailed data analysis is at Annex C. Use of a fine resolution clutter map would support detection of ac between suitably spaced turbines; to minimise the spacing required to achieve detection between turbines the resolution of the clutter cells should be the finest that is practicably achievable, that being the range and azimuth resolution of the radar. Due to the use of a composite aloft clutter map[5] in the T101[6], noise received in any of beams 2-7 will affect all of beams 2-7 equally. Therefore, **it is recommended that**:

(1) AD Radar processing should employ fine clutter maps (clutter map range resolution equal to radar range resolution) to minimise the area of impact of wind turbines on detection and support detection between turbines.

(2) Radar clutter-processing techniques should not allow detections in one beam to adversely affect the sensitivity of other beams.

b. Normal Radar – Background Averager. The Background Averager in the T101 continuously samples the received energy in a sliding window both in front of and behind each individual range cell as detailed in Annex D. Any significant radar reflector within the range covered by the Background Averager will influence the processing of the tgt cell. Wind turbines are known to be a significant source of clutter; previous measurements[7] indicated that the P&L Wind Turbine Farm was approximately 25dB[8] above ambient noise from this deployment site. This was expected to significantly raise the processing threshold for tgt cells up to 1 km from the edge of the wind farm[9]. This hypothesis was tested by setting the radar clutter map to only operate at ranges inside of the wind turbines, relative to the radar, leaving the Background Averager as the only significant clutter processing system. The resultant radar data is analysed in depth at Annex C. The remaining loss of detection extended approximately 2km either side of the wind turbines. This compares unfavourably to the expected Background Averager sliding window range of 1 km. It was impossible to conclude that the Background Averager sliding window was the sole source of reduced sensitivity once the clutter maps are removed. There are numerous factors that could have influenced these observations, not least of which were terrain and atmospheric conditions. The output of the Background Averager was also directly influenced by other system parameters to control the overall False Alarm Rate of the radar; these are influenced by factors outside of the sliding window. The Background Averager remains the most likely source of reduced sensitivity in this instance.

17. MTI Radar Channel. For the T101 Radar, the MTI channel operates independently of the clutter map process. It was only necessary to consider the impact of the Background Averager on the MTI channel. However, there were 2 key conditions under which the performance of the MTI channel had to be evaluated. These were the performance with the turbines in motion and

[5] The Aloft Clutter Map encompasses Beams 2-7.
[6] See Annex C.
[7] Attenuation measurements during an MoD ATC Radar Trial using a Watchman Radar on the same deployment site, looking at the same P&L Wind Turbine Farm.
[8] 315 times.
[9] The T101 Background Averager samples approximately 1 km from the target cell, a range comparable to other Radars.

static. When the turbines were static, the MTI channel performed as expected and was capable of detecting a low RCS ac (Hawk T Mk1A) throughout a radial flight profile (relative to the radar) over the wind turbines, regardless of altitude. With the turbines in motion the MTI channel failed to detect low RCS ac overhead and in close proximity to the turbines; ac with higher RCS (Dominie T Mk1A) were detected only at altitudes above 8000 – 12 000 ft AMSL[10]. The processing of the MTI channel was being de-sensitised when the turbines were in motion. This was consistent with expectations. The area affected by this desensitisation was less clearly bounded than the clutter map-based effects observed in the normal radar channel and was harder to evaluate. Detailed analysis, at Annex C, suggested that the effect was bounded at between 0.5 – 0.6 nm behind the turbines. The effect was less clearly bounded in front of the turbines, possibly because of airspace limitations on sortie profile design. The data was broadly consistent with the area observed behind the turbines. The Background Averager samples approximately 1 km away from the tgt cell. The data analysis supported the hypothesis that the loss of sensitivity was likely to be due to the Background Averager but did not conclusively prove this. Information provided by BAES Insyte indicated that potential technical solutions existed to reduce the disproportionate impact of large RCS objects, such as wind-turbines, on the overall output of the Background Averager. Detailed analysis of these solutions is beyond the scope of this report. Where radars are required to detect tgts in close proximity to, or directly overhead, wind turbines, **it is recommended that measures be considered to reduce the impact of large RCS objects in the Background Averager.**

18. <u>SSR</u>. Previous Air C2 OEU trials did not examine the impact of wind turbines on SSR. Protab Ltd assessed the performance of SSR during this Trial. The incidence of SSR reflections or corrupt/blank decodes was no greater during sorties over and around the wind turbines than for ac flying within the global coverage of the T101[11]. Failure to combine primary and SSR plots corresponding to the same ac (double plotting)[12] was frequently observed when trial ac flew over or close to the wind turbines. Subsequent analysis suggested that the incidence of double plotting was more dependent on ac aspect rather than the proximity of the ac to the wind turbines. Similarly, whilst some variation in radar primary height data was observed, subsequent analysis showed no significant difference in the performance over the turbines than that recorded globally. The analysis was limited by the reduced transmit sector and data link output. There was no evidence to suggest that the performance of SSR was affected by the presence of the wind turbines.

19. <u>Elevation Sidelobes</u>. Information provided by BAES Insyte, the Design Authority (DA) for the T101 Radar, suggests that the elevation sidelobes for the T101 were at least 25 dB less sensitive than the main lobe. As the T101 radar beam forms on both Transmit and Receive cycles, this produces an expected reduction in sensitivity of 50 dB (100 000 times) in the first elevation sidelobe. Previous measurements of the P&L turbines, taken from the same radar site used for this trial, place the returns from the turbines at greater than 20 dB (100 times) but less than 30 dB (1000 times) above the ambient noise level. The theoretical worst case should still result in reflected energy from the wind turbines in the first elevation sidelobe being less than 20 dB below ambient noise. This should be sufficient to suppress the returns and remove any possible effect. Observations made during this Trial supported the hypothesis, derived from the previous AD Radar Trial, that returns from the wind turbines were being detected in the elevation

[10] Indicating that the lowest MTI Beam, was unable to detect the target as it also had the turbines in its main-lobe.
[11] T101 coverage during the Trial was artificially limited to a 30º transmit sector and a maximum range of 120 data miles; this impacts on the ability to make comprehensive comparative evaluations of SSR data.
[12] In this context, 'double plotting' refers to those occasions where both primary and secondary radar returns were received from an individual ac but the radar system failed to combine them into a single plot. Double plotting was also observed when false returns from the turbines were incorrectly associated with SSR returns from an ac.

sidelobes, particularly those of the upper beams. More detailed information is at Annex C. Further analysis of this problem would require that the current sidelobe performance of the T101 antenna used for the Trial be measured in both Transmit and Receive beams. Ideally, this should be at a different facility to that used to produce the original beam patterns. Therefore, **it is recommended that the transmit and receive beam patterns of the T101 System used for this Trial be analysed, particularly the first elevation sidelobes.**

20. Elevation Nulls. Nulls occur naturally in any focused radar beam; the most obvious example of a null is the point of lowest sensitivity that occurs between the main-lobe and the first sidelobe. The apparent interference effects of wind turbines on the T101 were successfully removed during this Trial by using the Electronic Tilt feature of the radar to place a null (simultaneous for transmit and receive beams) over the wind turbines. Placing the first null of Beam 1 over the turbines allowed consistent detection of a Hawk T Mk1A in normal radar at all altitudes within the coverage of the beam. Some modern radar systems incorporate the ability to steer nulls in their beam structure, normally as an Electronic Warfare technique. Placing a null over a wind farm that is on or above the horizon relative to the radar would significantly affect long-range detection. In radar systems deployed for surveillance overhead wind turbines (as a gap-filler in a composite radar system) this offers a high likelihood of complete mitigation of the interference effects. This technique is discussed in more depth at Annex E. Therefore, **it is recommended that radars with steerable nulls in both their transmit and receive beams be considered a viable option for gap-filling overhead wind turbines.**

21. Turbine RCS. The P&L wind turbine farm is estimated to have an RCS of approximately 25 dBm^2; the RCS of current generation turbines proposed for off-shore developments could be as much as 1000 times greater, although 10-100 times is more likely[13]. Blade Flash RCS in the MTI channel was believed to be of similar order of magnitude as the overall structural RCS, particularly for the turbines under evaluation during this Trial[14]. The large RCS of wind turbines coupled with the blade flash effects from the moving turbines were believed to be highly significant factors that impact on radar systems. Any increase in turbine RCS is likely to increase the loss of sensitivity in radar systems that are within LoS of the turbines. Conversely, any decrease in turbine RCS is likely to decrease the loss of sensitivity. Both this Trial and the previous AD Radar Trial demonstrated that an increase in tgt RCS[15] of just 10-20 dBm^2 (Hawk T Mk1A to Dominie T Mk1A) could significantly increase the Probability of Detection (PD) of the radar overhead the wind turbines. Globally, several companies have proposed methods to reduce the effective RCS of wind turbines, most notably Vestas Blades UK Ltd (in collaboration with QinetiQ). The forecast RCS reduction is 10-20 dB. Therefore, **it is recommended that RCS reduction for wind turbines be regarded as a valid component of a composite solution to improve detection of low RCS ac overhead wind turbines**.

22. Composite Solution. The results discussed above relate to specific areas of the overall interference effects of wind turbines on AD Radar. The recommendations each address specific solutions and apply directly to the T101. The principles discussed are equally applicable when forecasting the effect of wind turbines on a generic AD Radar. To ensure mitigation of the interference effects it is necessary to consider all the factors observed during this Trial. It is likely that for an AD Radar to successfully detect and track overhead wind turbines it would require a composite of some or all of the techniques discussed. Therefore, **it is recommended that evaluation of the effects of wind turbines on current and future AD Radar take**

[13] No recorded measurements were available; modelling places the RCS at approximately 35-55 dB m^2.
[14] Based on separate measurements taken in normal and MTI channels during an ATC Radar Trial.
[15] The Trial could not change the RCS of the windfarms, therefore ac with a larger RCS were chosen to prove this theory.

account of Clutter Mapping, Background Averaging techniques, Beam Structure and Turbine RCS.

TRIAL OBJECTIVES SATISFIED

OBJECTIVE 1. RECORD UNPROCESSED, PULSE-TO-PULSE VIDEO PHASE HISTORY DATA FROM AN AD RADAR IN ITS DIFFERENT MODES OF OPERATION, AGAINST A VARIETY OF AC IN THE VICINITY OF WIND TURBINES

23. BAES Insyte, the DA for the T101 Radar, was invited to participate in this Trial in order to conduct pulse-to-pulse data recording (a capability not available within the MoD). This participation was not funded but was undertaken in support of other related tasks that BAES Insyte is conducting for the Department of Trade and Industry. OBJECTIVE FULLY SATISFIED

OBJECTIVE 2. COMPARE AC AND WINDFARM DIGITAL SCAN CONVERTER OUTPUT FOR EACH RECEIVER BEAM OF THE T101 RADAR UNDER ALL RELEVANT PERMUTATIONS OF PROCESSING AND FILTERING TECHNIQUES EMPLOYED BY THE SYSTEM.

24. The full range of sorties was conducted iaw the Trial Management Plan allowing all relevant permutations of radar set-up to be observed. OBJECTIVE FULLY SATISFIED

OBJECTIVE 3. PROVIDE GUIDANCE ON MITIGATION OF THE INTERFERENCE EFFECTS BETWEEN WIND TURBINES AND AD RADARS

25. Detailed guidance for MoD as a result of this Trial is contained at Annex E. OBJECTIVE FULLY SATISFIED

OBJECTIVE 4. RECORD RADAR DATA IN A FORM IN WHICH IT MAY SUBSEQUENTLY BE REPLAYED FOR DETAILED ANALYSIS

26. Both RADAC and DREAM were used to record the T101 Radar output during the Trial, supporting subsequent analysis. OBJECTIVE FULLY SATISFIED

ADDITIONAL OBSERVATIONS

27. T101 Configuration. In 1998, the T101 was modified by the DA to alter the way that clutter was processed. The system retained its original clutter map structure of one ground clutter map and one aloft clutter map. However, Beam 2 was altered from being solely a ground clutter beam to become largely an aloft clutter beam; further details are at Annex E. On the horizon (0º elevation), Beam 2 is reduced in gain to approximately one sixteenth of its peak[16]. However, a wind turbine farm at 0º elevation from the radar head would not be attenuated sufficiently for it to disappear below the ambient noise level[17], allowing energy reflected from the turbines to populate the clutter map (dependent on radar set-up). For an onshore wind turbine farm, the turbines will often be at elevations greater than 0º, exacerbating the problem. Low attenuation in any radar main lobe within LoS of wind turbines would reduce the sensitivity of the radar and lower the PD for any given ac. This would impact on the ability of any radar to detect tgts of interest above the clutter reflected from the wind turbines. Therefore, **it is**

[16] Approximately –12dB at 0º elevation.
[17] Total attenuation of 24dB for transmit and receive combined; wind turbines at P&L measured at 25-30dB above ambient noise.

recommended that consideration is given to the beam shape and antenna gain when evaluating the likely impact of wind turbines on AD Radar.

CONCLUSIONS

28. The results of this Trial supported the theories formed as a result of the previous AD Radar Trial and validated the recommendations made therein. The presence of a hole in detection at all levels overhead a wind turbine farm was shown to result from the presence of a large radar reflector (the wind turbines) in direct LoS of the radar antenna. The use of a coarse clutter map together with sharing of clutter maps between multiple beams significantly exacerbated the problem. Other clutter suppression circuitry, in this case the Background Averager, was also shown to have an effect. Where a radar beam was free of reflections from the wind turbines then it can detect and track even a low RCS ac such as the Hawk T Mk1A directly above the turbines; this can be achieved either by steering the beam or by focusing a null over the wind turbines. Whilst the results of this Trial are focused on the T101 Radar, they have established several key principles that can be applied when considering the vulnerability of any radar system to interference from wind turbines. Detailed analysis of SSR performance during the Trial showed no significant impact of wind turbines on SSR. The value of independent clutter processing in all beams of a 3-D Radar, coupled with a fine resolution clutter map, was demonstrated and should be considered a key requirement for effective AD Radar coverage in the proximity of wind turbine farms. A composite solution based on some or all of the areas discussed above offers the best likelihood of mitigating the impact of wind turbine farms on AD Radar.

RECOMMENDATIONS

MAJOR RECOMMENDATIONS

29. It is recommended that:

a. The MoD continues to closely examine the potential impact of any application for a wind turbine farm within radar LoS of an AD radar, regardless of range. (Para 14)

b. AD Radar processing should employ fine clutter maps (clutter map range resolution equal to radar range resolution) to minimise the area of impact of wind turbines on detection and support detection between turbines. (Para 16a (1))

c. Radar clutter-processing techniques should not allow detections in one beam to adversely affect the sensitivity of other beams. (Para 16a (2))

d. Measures be considered to reduce the impact of large RCS objects in the Background Averager. (Para 17)

e. The transmit and receive beam patterns of the T101 System used for this Trial be analysed, particularly the first elevation sidelobes. (Para 19)

f. Radars with steerable nulls in their transmit and receive beams be considered a viable option for gap-filling overhead wind turbines. (Para 20)

g. RCS reduction for wind turbines be regarded as a valid component of a composite solution to improve detection of low RCS ac overhead wind turbines. (Para 21)

h. Evaluation of the effects of wind turbines on current and future AD Radar take account of Clutter Mapping, Background Averaging techniques, Beam Structure and Turbine RCS. (Para 22)

i. Consideration is given to the beam shape and antenna gain when evaluating the likely impact of wind turbines on AD Radar. (Para 27c)

<Original signed>

D M WEBSTER
Squadron Leader
Officer Commanding
Static Ground Systems Operational Evaluation Squadron
Air C2 OEU

12 Aug 05

Annexes:

A. Sortie Timings and Profiles.
B. Manual Data Capture During this Trial.
C. Data Analysis.
D. T101 Background Averager and Clutter Maps.
E. Guidance on Mitigation of the Interference Effects Between Wind Turbines and AD Radars.

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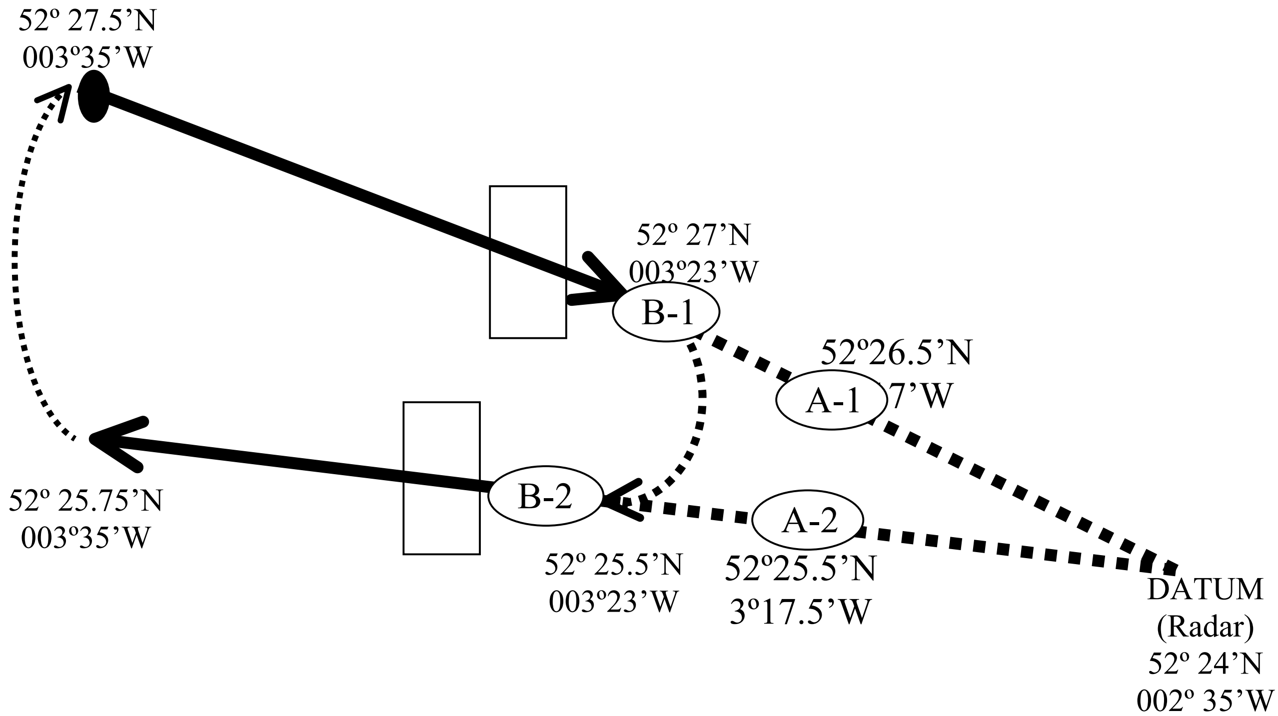
ANNEX A
DATED 12 AUG 05

SORTIE TIMINGS AND PROFILES

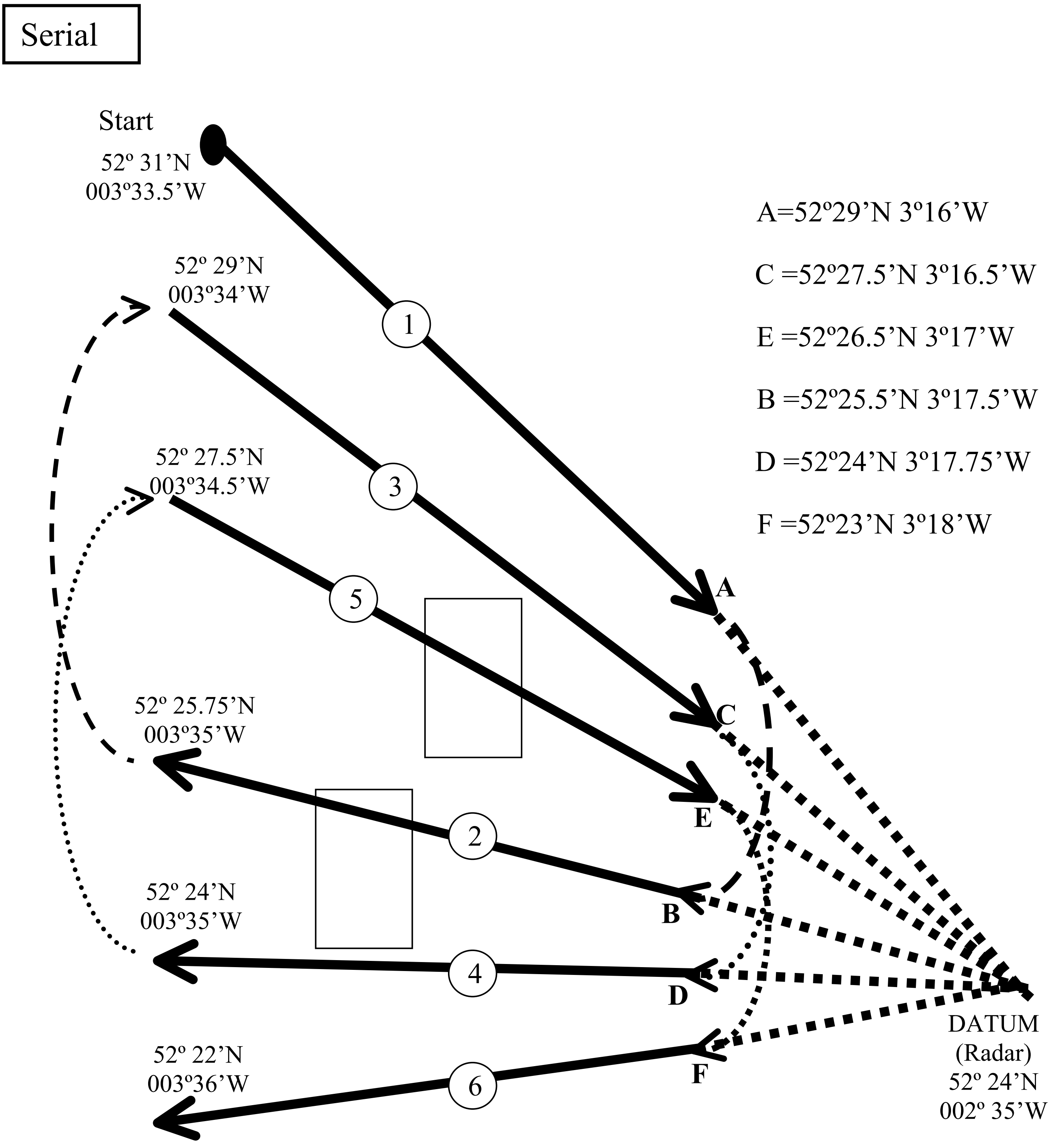
1. Profiles. The coordinates for the trial profiles are shown in the following diagrams:

Serial 1: A & B -



Height- Serial 1-A: 2000 ft; 5500 ft
- Serial 1-B: 8500 ft; 14 000 ft; 19 000 ft; 23 000 ft

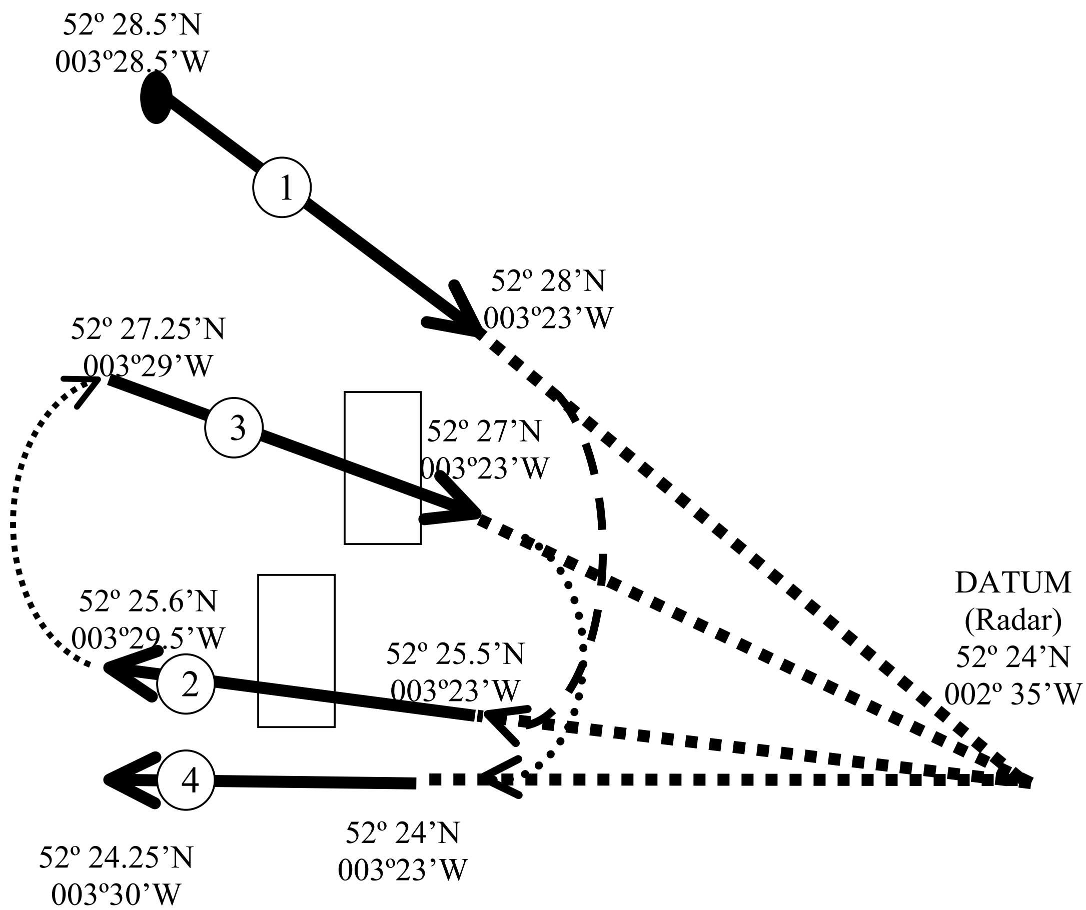
All Heights: AMSL, minimum desired height
(Pilot to use higher if required for safety of



Height - 2000 ft; 5500 ft

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

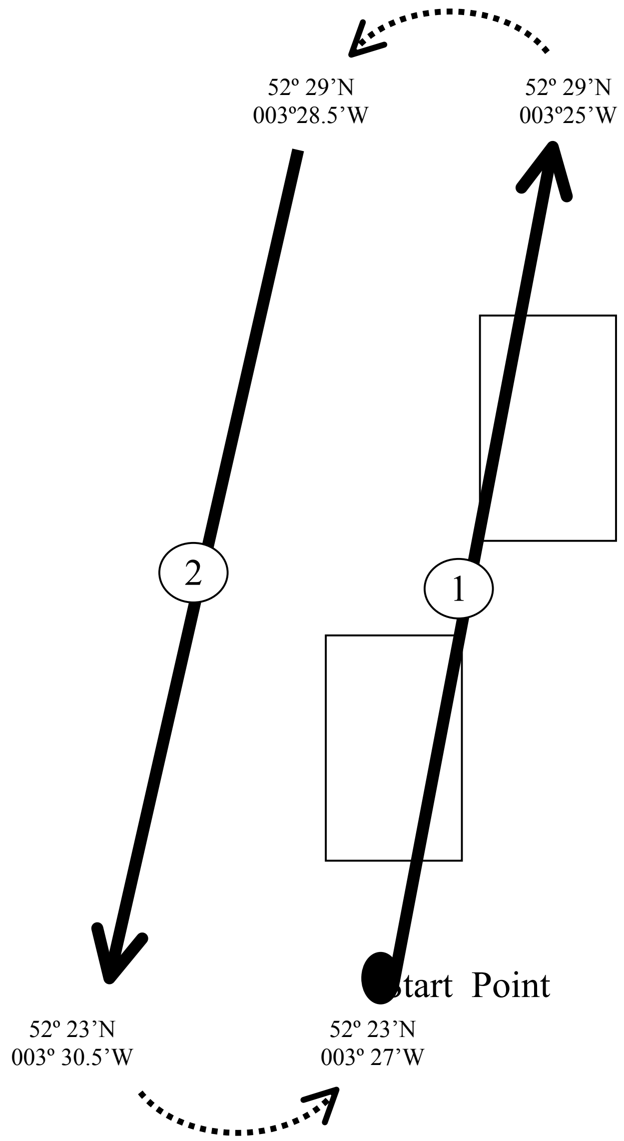
Serial



Height: 2000 ft; 5500 ft; 8500 ft; 14 000 ft; 19 000 ft; 23 000 ft

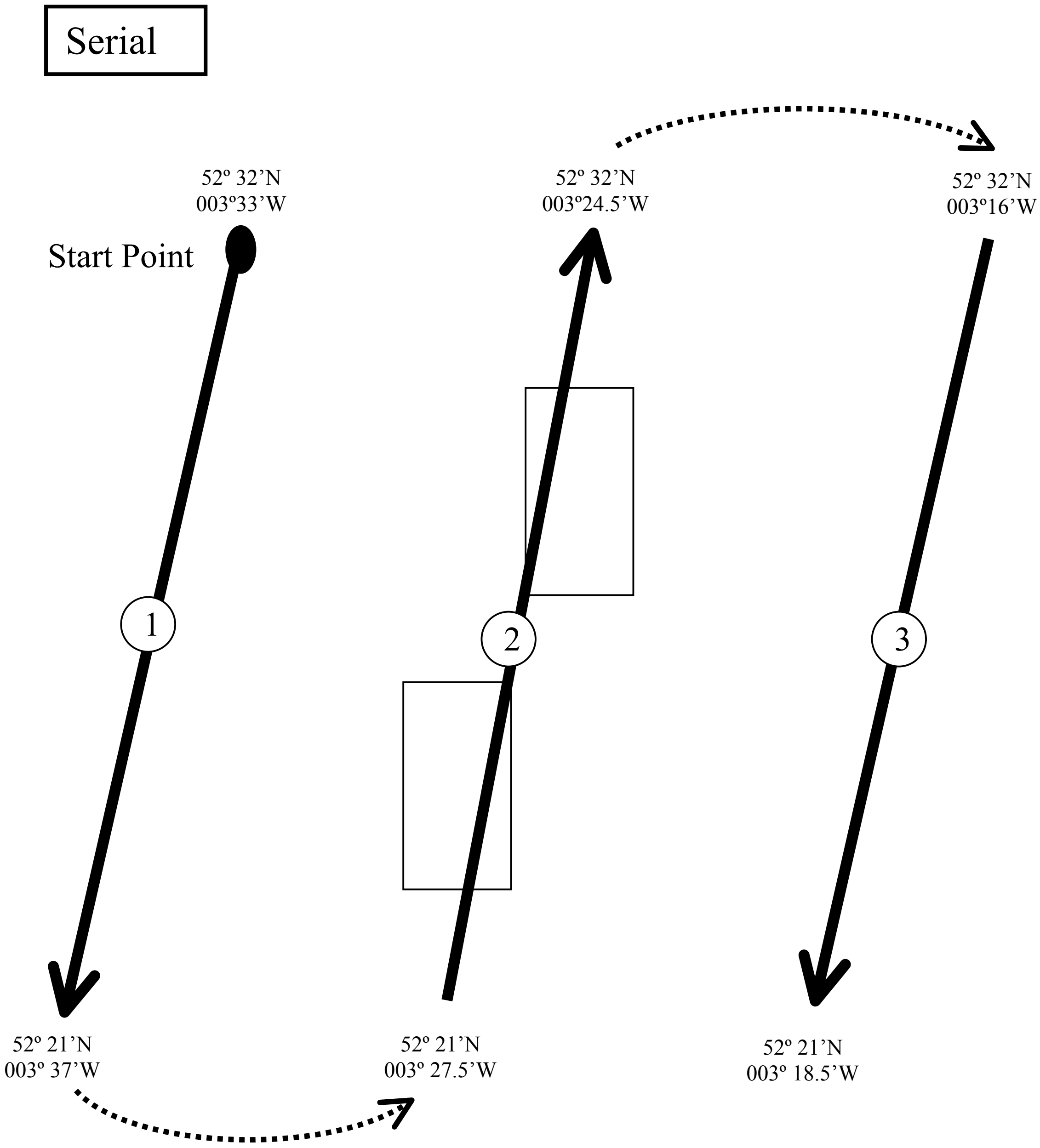
All Heights: AMSL, minimum desired height
(Pilot to use higher as required for safety of

Serial



Height: 2000 ft; 5500 ft; 8500 ft’; 14 000 ft; 19 000 ft; 23 000 ft

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



Height: Primary - 2000'; 5500'
Secondary (Leg 1& 2 Only) – 8500 ft; 14 000 ft; 19 000 ft; 23 000 ft

All Heights: - AMSL, minimum desired height
(Pilot to use higher as required for safety of flight)
- pilot to remain clear below airway on leg 3
- climb only in turn

ANNEX B
DATED 12 AUG 05

MANUAL DATA CAPTURE DURING TRIAL

Day One - 31 Mar 05	Flying Cancelled	Radar unserviceable		

Day 2 - 01 Apr 05 am	Morning flying cancelled	Weather unfit for ac		Wind farm data 0900Z Wind Speed 5.5 m/s Wind Direction NNW Turbines operating 55 RPM 43

Day 2 - 01 Apr 05 pm		Tucano T Mk1				Squawk: 3311		Wind farm data 1109Z Turbines operating Nil	
Time(ZULU)	**Serial Number/ Run no**	**T101 Processing:** GS= Ground & Sea RC= Rain & CHAFF							
1140	**4A/B / 1**	**Sector**	**Mode E Tilt**	**Normal R**	**MTI Thres**	**GC Thres**	**Aloft Cl Th**	**GCRange**	**ACRange**
	5500 ft	12/13/14	GS 0					21 nm	8
1146	Run 2	12/13/14	RC 0	0	84	0	0	8	8
Combined 25 nm, not combined over wind farm - SSR only until clear of the farm, combining at range 32 nm.									
1148	4 / 3	12/13/14	GS 0	0	84	0	0	8	8
Radar display very noisy with false plots 25-28 nm. No observations									
1155	Run 4	12/13/14	GS 0	4	80	4	0	50	8
Associated secondary plots over wind farm. Ground clutter Threshold at 4 made little difference									
1157	Run 5	12/13/14	GS 0	0	84	50	4	50	50
Combined plot range 37 to 31nm. No plots over wind farm									
1205	Run 6	12/13/14	GS	0	84	0	0	8	8
No combined plots over wind farm.									
1212	Run 7	12/13/14	GS	0	84	4	4	50	8
Looking at Aloft Clutter area only. Intermittent Secondary over wind farm. Plot disappearing at 31 nm, reappear at 29nm and combining.									
1221	Run 8	12/13/14	GS	4	84	4	0	50	8
As above comments time 1205.									
1225	Run 9	12/13/14	GS Tilt +2.25	0	84	0	0	8	8
With the +2 Tilt break through of raw radar and primary plots from wind farm. At +2.25 no break through was observed. ac combined.									
1236	Run 10	12/13/14	GS Tilt +2.0	0	84	0	0	8	8
At +2 Tilt false plots observed over wind farm with ac combining intermittently. Loss of ac at 30nm and combining at 31nm. Ac RTB AT 1238Z									

Day 2 - 1 Apr 05 pm		Hawk T Mk1A			squawk 3311		Wind farm Data 1320Z Wind speed 4 m/s Wind direction NW Turbines operating Nil RPM 0		
Radar Serviceable but 0.4º height error									
Time(Z)	**Serial Number/ Run no**	**T101 Processing:** GS= Ground & Sea RC= Rain & CHAFF							
		Sector	**Mode / Tilt**	**Normal R**	**MTI Thres**	**GC Thres**	**AC Thres**	**GCRange**	**ACRange**
1320	1B 23,000 ft	12/13/14	RC 0	0	0	0	0	50	50
Observed Secondary only									
1325	Run 2	12/13/14	RC 0	0	0	0	0	8	8

MTI Tracking over wind farm at 23000ft within MTI beams. No change to above processing for the rest of the sortie.
1328 Run 3 19 000 ft west to east 250 kts. Combined plot over wind farm.
1337 Run 4 14 000 ft 250 kts. Combined
1345 Run 5 8000 ft 250 kts Combined
1338 Run 6 8000 ft 250 kts Combined
1350 Run 7 5500 ft 250 kts Combined
1358 Run 8 5500 ft 250 kts Combined
1500 Run 9 2000 ft 330 kts Combined

<table>
<tr><td colspan="2">Day 3 - 4 April 05 am

Radar Serviceable</td><td colspan="3">Hawk T Mk1A</td><td colspan="3">squawk 3313</td><td colspan="2">Wind farm Data 0755Z
Wind speed 5 m/s
Wind direction SW
Turbines operating 103
RPM 43</td></tr>
<tr><td>Time(Z)</td><td>Serial Number/ Run no</td><td colspan="3">T101 Processing:
GS= Ground & Sea RC= Rain & CHAFF</td><td colspan="3"></td><td colspan="2"></td></tr>
<tr><td></td><td></td><td>Sector</td><td>Mode / Tilt</td><td>Normal R</td><td>MTI Thres</td><td>GC Thres</td><td>Aloft Cl Thr</td><td>GCRange</td><td>ACRange</td></tr>
<tr><td>0800</td><td>1A/B 23,000 ft</td><td>12/13/14</td><td>RC 0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>50</td><td>50</td></tr>
<tr><td colspan="10">Beam 5 MTI plotting OK.</td></tr>
<tr><td>0800</td><td>Run 2 19000 ft</td><td>12/13/14</td><td>RC 0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>8</td><td>8</td></tr>
<tr><td colspan="10">Radar detecting and plotting ok.</td></tr>
<tr><td colspan="8">0805 Run 3 at 14 000 ft plotting ok
0814 Run 4 at 8500 ft loss for 2 scans over wind farm
0820 Run 5 at 5500 ft loss of tgt over wind farm
0829 Run 6 at 5500 ft repeat of run 5 for video
0835 Run 7 at 2000 ft Secondary only over wind farm.</td><td colspan="2">Wind farm Data 0830Z
Wind speed 7.6 m/s
Wind direction SW
Turbines operating 98
RPM 43</td></tr>
<tr><td>0838*</td><td>Run 8 2000ft</td><td>12/13/14</td><td>GS 0</td><td>84</td><td>0</td><td>0</td><td>0</td><td>8</td><td>8</td></tr>
<tr><td colspan="10">*Note change of mode to GS at 0838 MTI only- loss of tgt over wind farm</td></tr>
<tr><td colspan="10">0842 Run 9 2000 ft AMTI in. Secondary only over wind farm.
0845 Run 10 now in RC at 5500 ft combining over wind farm. Ac RTB at 0950.</td></tr>
</table>

Day 3 - 4 April 05 am Radar Serviceable		Dominie T Mk1A			Squawk 0442 On task 0848Z			Wind farm Data 0850Z Wind speed 7.5 m/s Wind direction SW Turbines operating 98 RPM 43	
Time(Z)	**Serial Number/ Run no**	**T101 Processing:** GS= Ground & Sea RC= Rain & CHAFF							
	4	**Sector**	**Mode / Tilt**	**Normal R**	**MTI Thres**	**GC Thres**	**Aloft Cl Thr**	**GCRange**	**ACRange**
0848	1900 ft	12/13/14	GS 0	0	84	0	0	8	8

Run 1. South to north, plot not combining over wind farm. Observed secondary and primary but not associating.
Run 2. North to south, at 1800 ft. Unassociated primary plot.
Run3. South to north, MTI now 0 Normal Threshold at 84. observing MTI.
Run 4. North to south, plot not combining over northern section of wind farm.
Run 5. Time 0915Z South to North, Ground and Aloft Clutter to range 50nm. Tgt at 1900 ft looking at AMTI. Plot intermittent.
Run 6. North to South, tgt at 1700 ft, combined throughout.
Run 7. South to north, tgt at 2000 ft primary only over wind farm.
Run 8. North to south, tgt repositioned to fly south leg 1.5 nm nearer to the wind farm. Combined throughout.

Wind farm data. 0930Z No change.
Time 0930 Now in Rain and Chaff mode
Run 9. South to north, tgt at 5500 ft and intermittent over wind farm.
Run 10 Combining throughout.
Time 0935Z Ground and Aloft clutter range to 8 nm.
Run 11. Combining throughout.
Run 12. Combining throughout.
Time 0945 tgt now at 2000 ft
Run 13. South to north. Tgt not combining then disappears over wind farm.
Run 14. North to south, some loss of tgt over wind farm.
Run 15. South to north, combining.
Time 1005Z Ground and aloft Clutter range to 50 nm to look at MTI.
Run 16. South to north, combining.

Run 17. North to south, loss of primary and then intermittent. **Time 1010Z Ground Threshold to 5, MTI Threshold to 84. Ac at 2100 ft**. Run 18. South to north, loss of primary plots over wind farm. Run 19. North to south, combining throughout. Run 20. South to north, secondary only for 2 scans. **Time 1018Z, MTI Threshold now 4. 5500 ft.** Run 21. North to south, combining. Run 22. South to north, combining. Ac RTB AT 1024.

<table>
<tr><td colspan="2">Day 3 - 4 April 05 pm

Radar Serviceable</td><td colspan="3">Hawk T Mk1A</td><td colspan="2"></td><td colspan="3">Wind farm data 1100Z
Wind speed 8.5 m/s
Wind direction WSW
Turbines operating 101
RPM 43</td></tr>
<tr><td>Time(Z)</td><td>Serial Number/ Run no</td><td colspan="3">T101 Processing:
GS= Ground & Sea RC= Rain & CHAFF</td><td colspan="2"></td><td colspan="3"></td></tr>
<tr><td></td><td></td><td>Sector</td><td>Mode / Tilt</td><td>Normal R</td><td>MTI Thres</td><td>GC Thres</td><td>Aloft Cl Thr</td><td>GCRange</td><td>ACRange</td></tr>
<tr><td colspan="10">
4 Apr 05. Afternoon sortie, Hawk time on task 1100Z for BAES Insyte profiles at 2000 ft.
Radar placed in various positive tilt positions for BAES Insyte data capture.</td></tr>
</table>

Day 3 - 4 April 05 pm Radar Serviceable		Dominie T Mk1A		Squawk 0246 On task 1320Z			Wind farm data 1330Z Wind speed 8.4m/s Wind direction SW Turbine operating 93 RP< 43		
Time(Z)	**Serial Number/ Run no**	**T101 Processing:** GS= Ground & Sea RC= Rain & CHAFF							
	Serial 4	**Sector**	**Mode / Tilt**	**Normal R**	**MTI Thres**	**GC Thres**	**Aloft Cl Thr**	**GCRange**	**ACRange**
1320Z	1900 ft	12/13	GS 0	2	2	7	5	50	50

Run 1. North to south, Uncombined plot with secondary only over mid point of wind farm.
Run 2. South to north, at 2000 ft, Uncombined plot with secondary only over mid point of wind farm.
Time 1330Z. Normal radar Threshold 84 Ground Clutter and aloft clutter range to 50 nm.
Run 3. North to south, combined throughout.
Run 4. South to north, combined throughout.
Time 1335Z. Normal radar Threshold 1, Ground Clutter Threshold 10.
Run 5. At 1900 ft plot combining.
Run 6. South to north, intermittent plots.
Time 1345Z. Ground clutter threshold 25,aloft clutter threshold 30.
Run 7. North to south, 1800 ft, combined then secondary only over wind farm.
Run 8. South to north, Secondary only.
Time 1348Z. Normal radar threshold 84, MTI Threshold 10.
Time 1350Z Radar fault. Rectified at 1401Z

		Sector	**Mode / Tilt**	**Normal R**	**MTI Thres**	**GC Thres**	**Aloft Cl Thr**	**GCRange**	**ACRange**
1401Z		12/13	GS 0	0	0	10	8	56	39

Restart runs at 1414Z Serial 4, 2000 ft.
Run 9. North to south, combined throughout.
Run 10. South to north, Secondary plots only over wind farm.
Run 11. North south ac at 5500 ft. Combined plots with one secondary only at mid point.
Run 12. South to north, combined throughout.
Time 1425Z Aloft clutter range to 21 nm.

Run 13 and 14 combined plots throughout. **1440Z MTI to 0** Run 15. North to south, combining. Run 16. South to north, loss of primary over wind farm. Run 17 to 20 at 1800 ft with MTI threshold at 1, 2 then 3. little change **Ac RTB AT 1510Z**	Wind farm data. 1450Z Windspeed 9 m/s Wind Direction WSW Turbines operating 101 RPM 43

Day 4 - 5 April 05 am Radar Serviceable		Tucano T Mk1		Squawk 3314			Wind farm Data 0745Z Wind speed 11.7 m/s Wind direction SW Turbines operating 100 RPM 43	
Time(Z)	**Serial Number/ Run no**	**T101 Processing:** GS= Ground & Sea RC= Rain & CHAFF						
	4	**Sector**	**Mode / Tilt**	**Normal R**	**MTI Thres**	**GC Thres**	**Aloft Cl Thr**	**GCRange**	**ACRange**
	14000 ft	11/12/13	GS 0	3	3	10	8	40	40

0745 on task.
0745 South to north, decombining over wind farm.
0748 North to south, combining.
0753 MTI to 0
0753 South to north, decombining over wind farm with Secondary only over north farm. Combined once clear of wind farm.
0756 North to south, combining.
0800 ac to 8500 ft
0801 South to north, Secondary, combined for 2 scans then plot jumping before combining at the north end of wind farm.
0805 Normal radar threshold to 84, GC and AC ranges to 8 nm. Looking at MTI only.
0807 North to south, Secondary for one scan then combined.
0810 South to North, Secondary only over wind farm.
0815 North to south, combined.
0819 Ac to 2000 ft
0819 South to north, secondary, combining once clear of wind farm.
0823 North to south, combining, ac RTB at 0827.

Day 4 - 5 April 05 am Radar Serviceable	Hawk T Mk1A	Squawk: 3313	Wind farm Data 0849Z Wind direction SW Wind speed 10.7m/s Turbines operating 97 RPM 43
Time(Z)	**Serial Number/ Run no**	**T101 Processing:** GS= Ground & Sea RC= Rain & CHAFF	

	23000 ft.	**Sector**	**Mode / Tilt**	**Normal R**	**MTI Thres**	**GC Thres**	**Aloft Cl Thr**	**GCRange**	**ACRange**
	1 B	11/12/13	RC 0	3	3	0	0	8	8

0841 East to west, loss of ac over wind farm beam 5.
0850 West to east at 19 000 ft, loss to ac over wind farm in beam 4.
0855 East to west at 19 000 ft, loss of ac over wind farm in beam 4.
0857 West to east at 14 000 ft, combined the loss of ac over wind farm.
0901 East to west at 14 000 ft, Secondary only over wind farm.
0903 West to east at 8500 ft, secondary only over wind farm
0905 East to west at 8500 ft, Secondary only over wind farm.
0910 West to east at 5500 ft, secondary only over wind farm.
0912 East to west at 5500 ft, secondary only over wind farm.
0917 West to east at 2000 ft, Secondary only over wind farm. **Squawk now 7001**
0923 Now Ground and Sea mode.
0923 West to east at 2000 ft, secondary only over wind farm.
0928 Serial 4 start at 2000 ft
0928 South to north, secondary only over wind farm.
0930 Now Rain and Chaff mode
0930 North to south, secondary only over wind farm.
0933 Ac to 5500 ft.
0933 South to north, secondary only over wind farm. **Squawk 3312.**
0940 Ac now at 14000 ft.
0940 North to south in front of wind farm, secondary only.
0943 RTB.

<table>
<tr><td colspan="2">Day 4 - 5 April 05 am

Radar Serviceable</td><td colspan="2">Tucano T Mk1</td><td colspan="4"></td><td colspan="2" rowspan="2">Wind farm Data 1022Z
Wind direction SW
Wind speed 8.9m/s
Turbines operating 100
RPM 43</td></tr>
<tr><td>Time(Z)</td><td>Serial Number/ Run no</td><td colspan="3">T101 Processing:
GS= Ground & Sea RC= Rain & CHAFF</td><td colspan="3"></td></tr>
<tr><td></td><td>Serial</td><td>Sector</td><td>Mode / Tilt</td><td>Normal R</td><td>MTI Thres</td><td>GC Thres</td><td>Aloft Cl Thr</td><td>GCRange</td><td>ACRange</td></tr>
<tr><td></td><td>1 A/B</td><td>11/12/13</td><td>GS 0</td><td>0</td><td>84</td><td>3</td><td>0</td><td>50</td><td>50</td></tr>
<tr><td colspan="10">1011 West to east at 23 000 ft, ac plot not combining
1016 East to west at 19 000 ft, decombining over wind farm.
1020 Processing change aloft clutter threshold now 60 to check noise level. Then changed to 0.
1023 West to east, loss of primary over wind farm.
1027 East to west, 14 000 ft, loss of primary over wind farm.
Normal radar to 1. Radar processing problem. Radar back at 1138.</td></tr>
<tr><td>Processing change</td><td>Serial</td><td>Sector</td><td>Mode / Tilt</td><td>Normal R</td><td>MTI Thres</td><td>GC Thres</td><td>Aloft Cl Thr</td><td>GCRange</td><td>ACRange</td></tr>
<tr><td></td><td>1 A/B</td><td>11/12/13</td><td>GS 0</td><td>0</td><td>84</td><td>8</td><td>6</td><td>50</td><td>50</td></tr>
<tr><td colspan="5">1045 West to east 8500 ft. Loss of plot over wind farm.
1048 East to west 8500 ft. Not combining over wind farm.
1057 West to east 5500 ft. No combined plots over wind farm.
1100 East to west 5500 ft. Secondary only over wind farm.
1108 West to east 2000 ft. Secondary only over wind farm.</td><td colspan="5">Wind farm Data 1140Z 1320Z
Wind direction SW SW
Wind speed 10m/s 6 m/s
Turbines operating 101 60
RPM 43 43</td></tr>
<tr><td>Processing change</td><td>Serial</td><td>Sector</td><td>Mode / Tilt</td><td>Normal R</td><td>MTI Thres</td><td>GC Thres</td><td>Aloft Cl Thr</td><td>GCRange</td><td>ACRange</td></tr>
<tr><td></td><td>4</td><td>11/12/13</td><td>GS +2</td><td>0</td><td>84</td><td>8</td><td>0</td><td>50</td><td>50</td></tr>
<tr><td colspan="10">1118 Processing tilt change to check beam 2 over wind farm. Tucano at 5500 ft. Some losses of primary, ok once clear of wind farm.
1129 North to south. Secondary only over wind farm.
1141 E Tilt at +3. Loss of tgt over windfarm</td></tr>
</table>

<table>
<tr><td colspan="2">Day 5 - 6 April 05 am

Radar Serviceable</td><td colspan="2">Hawk T Mk1A</td><td colspan="4">Squawk: 3313</td><td colspan="3" rowspan="2">Wind farm Data 0750Z
Wind speed 8.9 m/s
Wind direction SW
Turbines operating 101
RPM 43</td></tr>
<tr><td>Time(Z)</td><td>Serial Number/ Run no</td><td colspan="4">T101 Processing:
GS= Ground & Sea RC= Rain & CHAFF</td><td colspan="2"></td></tr>
<tr><td></td><td></td><td>Sector</td><td>Mode / Tilt</td><td>Normal R</td><td>MTI Thres</td><td>GC Thres</td><td>Aloft Cl Thr</td><td>GCRange</td><td>ACRange</td><td></td></tr>
<tr><td></td><td>4</td><td>11/12/13</td><td>GS +2.5</td><td>2</td><td>2</td><td>10</td><td>8</td><td>52</td><td>52</td><td></td></tr>
<tr><td colspan="11">0850 Looking for ac plot at 22 000 ft in beam 5.
0905 Tilt now +3. Ac climbing to 23 000 ft to be in centre of beam.
Rain and Chaff mode Still able to see clutter on raw video.
0914 Tilt to +5.75 Beam 2 first sidelobe on the wind farm. Beam 6 and 7 no wind farm paints.
0918 Tilt to +3. Wind farm seen in beam 1, 2 and 3. Beam 4 producing raw video.
0927 Ac to 18 500 ft Beam 2. Loss of combined over wind farm.
0936 Ac to 12 000 ft, ac in centre of beam one. Combined plots throughout.
0946 South to north, combined.
0949 North to south combined.
0951 South to north 8000 ft combining throughout.
0954 Tilt to +2.5 ac at 6000 ft at combined with loss of one scan. Ac RTB at 0958.</td></tr>
</table>

<table>
<tr><td colspan="2">Day 5 - 6 April 05 pm

Radar Serviceable</td><td colspan="2">Hawk T Mk1A</td><td colspan="4">Squawk: 3313</td><td colspan="2" rowspan="2">Wind farm Data 1120Z
Wind speed 14.5m/s
Wind direction SW
Turbines operating 101
RPM 43</td></tr>
<tr><td>Time(Z)</td><td>Serial Number/ Run no</td><td colspan="3">T101 Processing:
GS= Ground & Sea RC= Rain & CHAFF</td><td colspan="3"></td></tr>
<tr><td></td><td></td><td>Sector</td><td>Mode / Tilt</td><td>Normal R</td><td>MTI Thres</td><td>GC Thres</td><td>Aloft Cl Thr</td><td>GCRange</td><td>ACRange</td></tr>
<tr><td></td><td>4</td><td>11/12/13</td><td>RC 0</td><td>84</td><td>0</td><td>0</td><td>0</td><td>50</td><td>50</td></tr>
</table>

Looking at the effect in MTI beams.

1124 Beam 9 ac at 17 000ft and seeing wind farm.
Beam 8 seeing wind farm but no ac.
Beam 10 seeing wind farm
Ac at south point to start running north and combining throughout at 17 000 ft.
1133 North to south, combining throughout.
1137 South to north, combining throughout.
1138 Tilt +3, ac not seen in beam 8 but seen in beam 9
1140 Tilt +4, ac seen in beam 8 not in beam 9.
1141 ac to 5000 ft.
1143 Processing now 0 Tilt Normal radar 1 MTI threshold 0, Ground clutter threshold 25, aloft clutter 25, GC and ACRange 25 nm.
1143 South to north, ac not combining over wind farm.
1147 **Tilt to +1** (15db point) raw video can see everything Video on to record individual beams.
1153 **Tilt to +2.** Beam 2 clear of wind farm ac secondary only.
1157 South to north, secondary only.
1159 Ac to 6000 ft, observe in beam 1. Wind farm returns stronger in this configuration.
1201 South to north, secondary only.
1202 **Tilt to +2.25** raw video showing top of wind farm.
1203 **Tilt to +2.5** nothing in beam ac climbing to 7500 ft.
1204 Ac to 8000 ft over wind farm, secondary only.
1209 Now looking at MTI OUT normal radar 1, MTI to 84. Not picking up ac but seeing wind farm.
1214 **Aloft Clutter map out to 50nm**. Ac combined plot.
1222 South to north, combining over wind farm.
1226 north to south at 7500 ft, combining over wind farm.

1228 Tilt to 2.25, ac combining over wind farm. 1234 Tilt +2 (beam1) wind farm present ac decombining over wind farm. 1244 South to north, ac secondary only over wind farm. 1249 ac RTB.

<table>
<tr><td colspan="2">Day 5 - 6 April 05 pm

Radar Serviceable</td><td colspan="2">Dominie T Mk1A</td><td colspan="4">Squawk: 3313</td><td colspan="3" rowspan="2">Wind farm Data 1320Z
Wind speed 18m/s
Wind direction SW
Turbines operating 101
RPM 43</td></tr>
<tr><td>Time(Z)</td><td>Serial Number/ Run no</td><td colspan="3">T101 Processing:
GS= Ground & Sea RC= Rain & CHAFF</td><td colspan="3"></td></tr>
<tr><td></td><td></td><td>Sector</td><td>Mode / Tilt</td><td>Normal R</td><td>MTI Thres</td><td>GC Thres</td><td>Aloft Cl Thr</td><td>GCRange</td><td>ACRange</td><td></td></tr>
<tr><td></td><td>4</td><td>11/12/13</td><td>RC 0</td><td>1</td><td>84</td><td>8</td><td>0</td><td>50</td><td>50</td><td></td></tr>
<tr><td colspan="11">1342 Ac seen in beam 3, 4 and 5.
1350 Aloft clutter threshold to 84, ac not seen
1351 Normal radar threshold 10
1401 Aloft clutter threshold to 0.
1405 Changing to radials profile
1408 Aloft clutter to 84. Ac running west to east and combining. No effect from change of threshold.
1410 Ac to 19 000 ft nil effect.
Tilt to +1 Aloft clutter to 0.
1450 Ac RTB.</td></tr>
</table>

1ACC Deployment Forecast Validity 04 April 05 at 1200Z

Height	**Temperature**	**Pressure MB**	**Relative Humidity %**	**Wind**
MSL	PS 11	1020	58	260 05
1000	PS 07	982	60	270 10
2000	PS 04	946	68	270 10
3000	PS 04	911	83	270 15
4000	MS 01	875	85	270 20
5000	MS 03	843	78	270 20
10000	MS 12	691	91	270 35
15000	MS 19	566	91	220 50
20000	MS 27	459	95	210 60
25000	MS 38	369	91	210 60
30000	MS 50	294	59	210 70
35000	MS61	232	32	210 60
40000	MS 57	182	04	230 35
50000	MS 57	113	03	260 20
55000	MS 58	89	02	250 20
60000	MS 58	69	02	250 25

* All heights in feet AMSL.

Forecast Validity 05 April 2005 at 1200Z

Height	Temperature	Pressure MB	Relative Humidity %	Wind
MSL	PS 09	1023	70	230 10
1000	PS 06	982	72	230 15
2000	PS 03	946	80	240 20
3000	PS 01	913	89	240 25
4000	MS 01	877	83	250 25
5000	MS 02	843	81	250 25
10000	MS 13	692	99	240 15
15000	MS 20	566	90	270 35
20000	MS 27	460	94	270 55
25000	MS 38	369	98	270 65
30000	MS 51	294	96	280 80
35000	MS 59	231	33	280 70
40000	MS 56	182	03	270 45
50000	MS 58	113	03	270 30
55000	MS 60	89	03	260 25
60000	MS 62	69	03	260 20

Forecast 6 April 05 at 1200Z

Height	Temperature	Pressure MB	Relative Humidity %	Wind
MSL	PS 15	1005	53	240 15
1000	PS 10	968	51	250 20
2000	PS 07	933	60	250 25
3000	PS 04	896	69	250 30
4000	PS 02	863	77	250 30
5000	PS 01	832	61	250 35
10000	MS 11	683	30	250 40
15000	MS 19	560	08	240 50
20000	MS 30	454	14	240 90
25000	MS 41	364	21	230 80
30000	MS 50	290	07	240 90
35000	MS54	229	04	240 75
40000	MS 53	181	03	250 55
50000	MS 55	89	02	260 35
55000	MS 58	89	02	260 35
60000	MS 60	69	03	260 35

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DATA ANALYSIS

LOSS OF DETECTION IN NORMAL RADAR CHANNEL

1. Introduction. It is difficult to present the radar data from this Trial in a format which is compatible with a written report. However, the following graphs have been produced using MS Excel as a tool to convert the plot data recorded from the SDO/1000 protocol radar data link output and present them as an X,Y Cartesian graph. Both axes are presented as nautical miles (nm – 1 nm=1852 m) from origin; where origin is the radar antenna.

2. Clutter Maps. Figure 1 represents a composite plot picture from a Tucano T Mk1 sortie lasting approximately 100 min. This sortie was designed to provide bulk data in support of both analysis and pictorial representation of the obscuration of radar coverage by wind turbines. The radar was operated with the MTI Channel removed through the application of 84 dB[18] attenuation; the clutter ranges for both ground and aloft Clutter Maps were set to 92.6 km (50 nm). The majority of the 103 turbines were turning. It is apparent by visual inspection that the incidence of combined (coincident primary and SSR) radar returns is significantly reduced in the vicinity of, and overhead, the wind turbines.

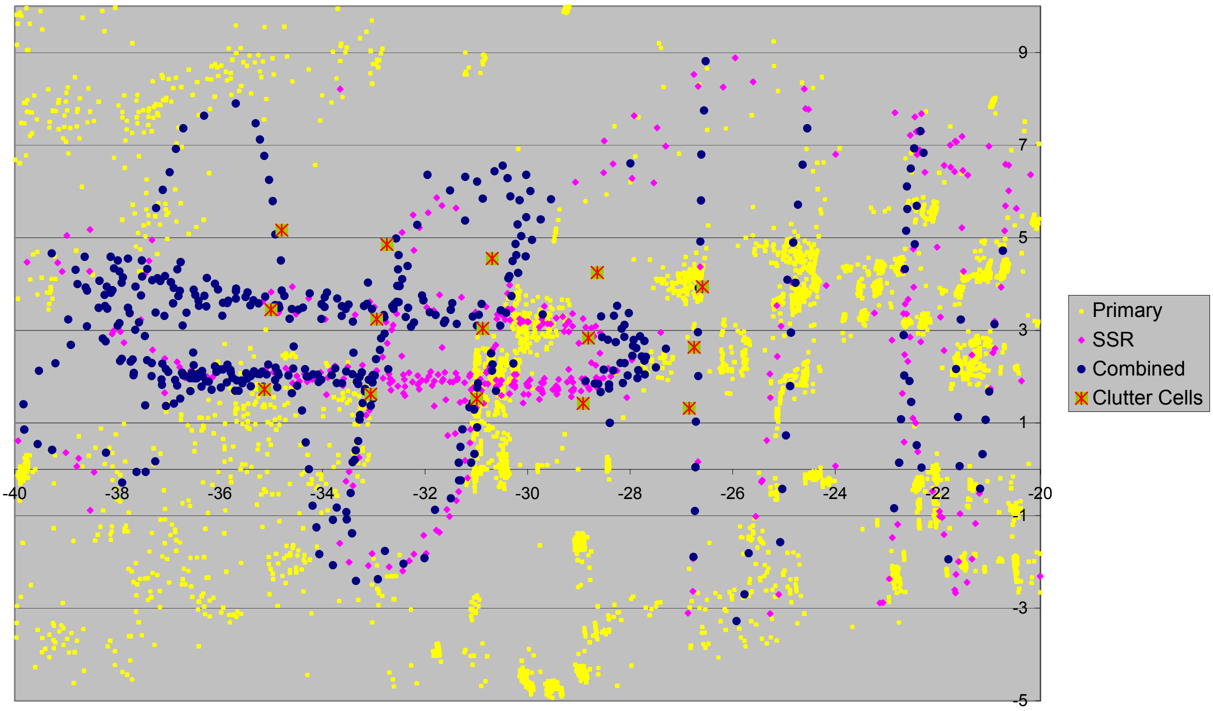


Figure 1 - T101 Radar Data - Tucano in Normal Radar

3. At Figure 2, the area around the wind turbines has been enlarged and the clutter cell boundaries overlaid (in blue). Numbering of the clutter cells (A09-A12 and B09-B12) is arbitrary and to aid discussion of the results.

[18] 2.5×10^8.

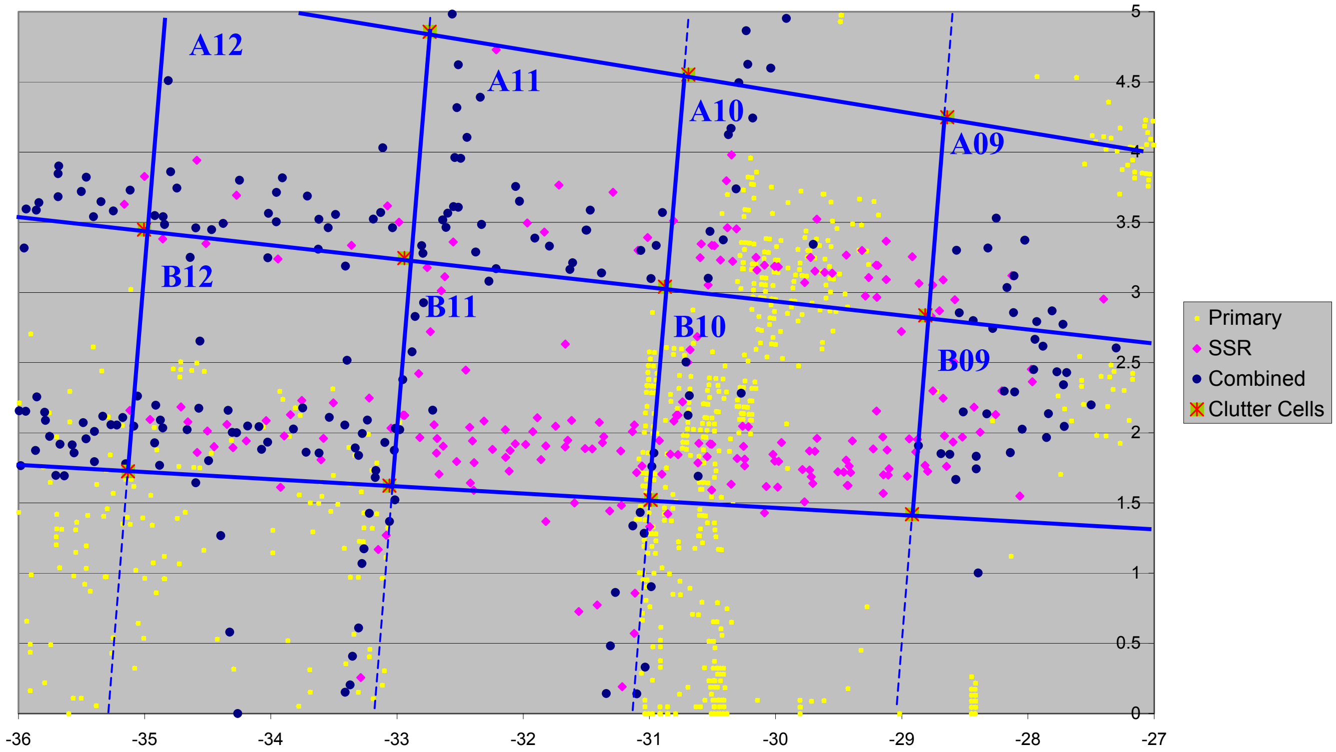


Figure 2 - T101 Radar Data - Tucano in Normal Radar

From Figure 2, within cells A10, B10 and B11 there is almost complete loss of plot combination. The lack of unassociated primary radar responses coincident with the SSR returns, indicates that primary detection was severely degraded in these cells. Within A09, A12, B09 and B12 there is a mixture of combined and 'SSR Only' returns from the Tucano T Mk1; PD within these cells was slightly reduced but attenuation was not as severe as in the 3 cells that contain wind turbines.

4. <u>Evidence</u>. Following the previous AD Radar Trial, we formed the hypothesis:

> H_0 – Loss of detection in the Normal Radar channel in the vicinity of wind turbines is due to the action of the Clutter Maps.

The data at Figure 2 strongly supports this hypothesis; it remains the considered opinion of the Air C2 OEU that loss of primary coverage in Normal Radar in the vicinity of wind turbines is the result of raised thresholds in the T101 Clutter Map. This problem is exacerbated by the use of coarse clutter map cells.

5. <u>Background Averager</u>. To assess the impact of the Background Averager in the Normal Radar channel, it was necessary to set the Ground and Aloft Clutter Ranges inside the range to the wind turbines. Having done this, the following coverage plots were obtained:

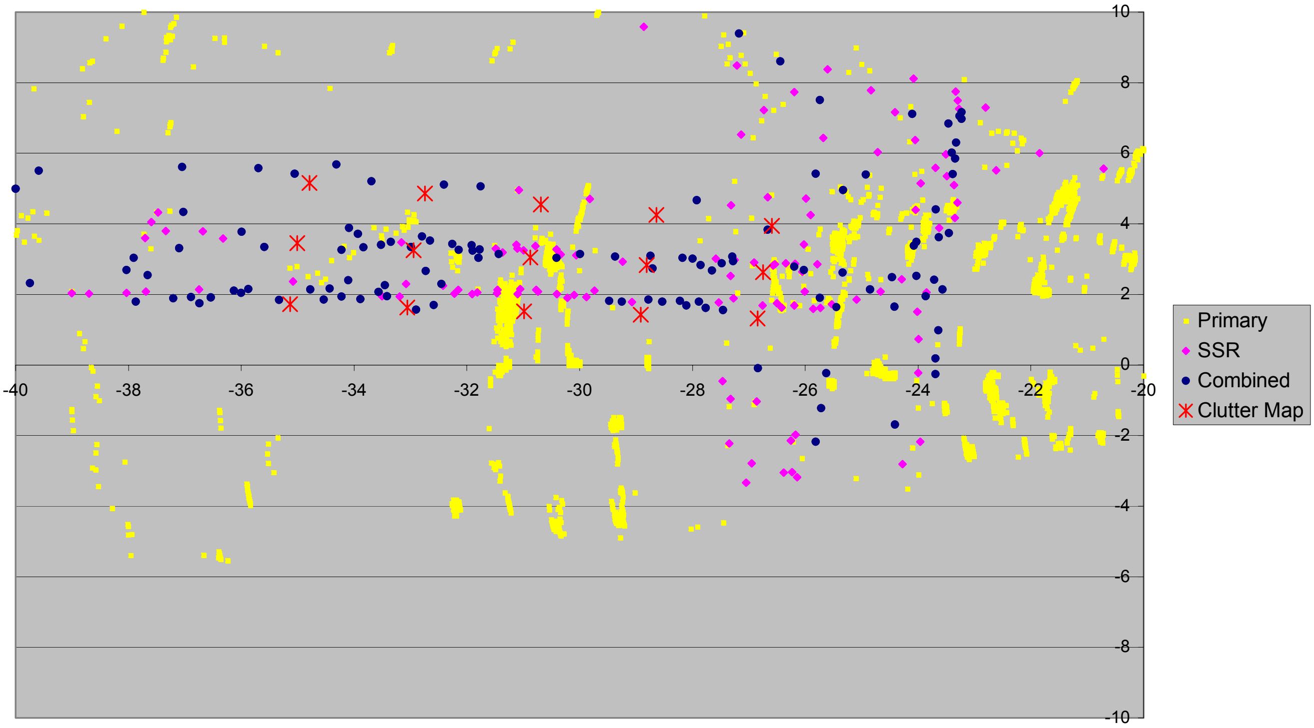


Figure 3 - T101 Radar Data - Tucano in Normal Radar (no turbines turning)

The area over and around the turbines within which detection was affected no longer corresponds to the location of the Clutter Map cells; this result was consistent with the radar set-up.

6. If the area around the wind turbines is enlarged we obtain the image at Figure 4, below. The lateral bounds of the Background Averager have been added in red to indicate the possible extent of the wind turbines influence in the Background Averager sliding window; finally, the blue overlay lines indicate the range beyond which there is a significant increase in the observed PD.

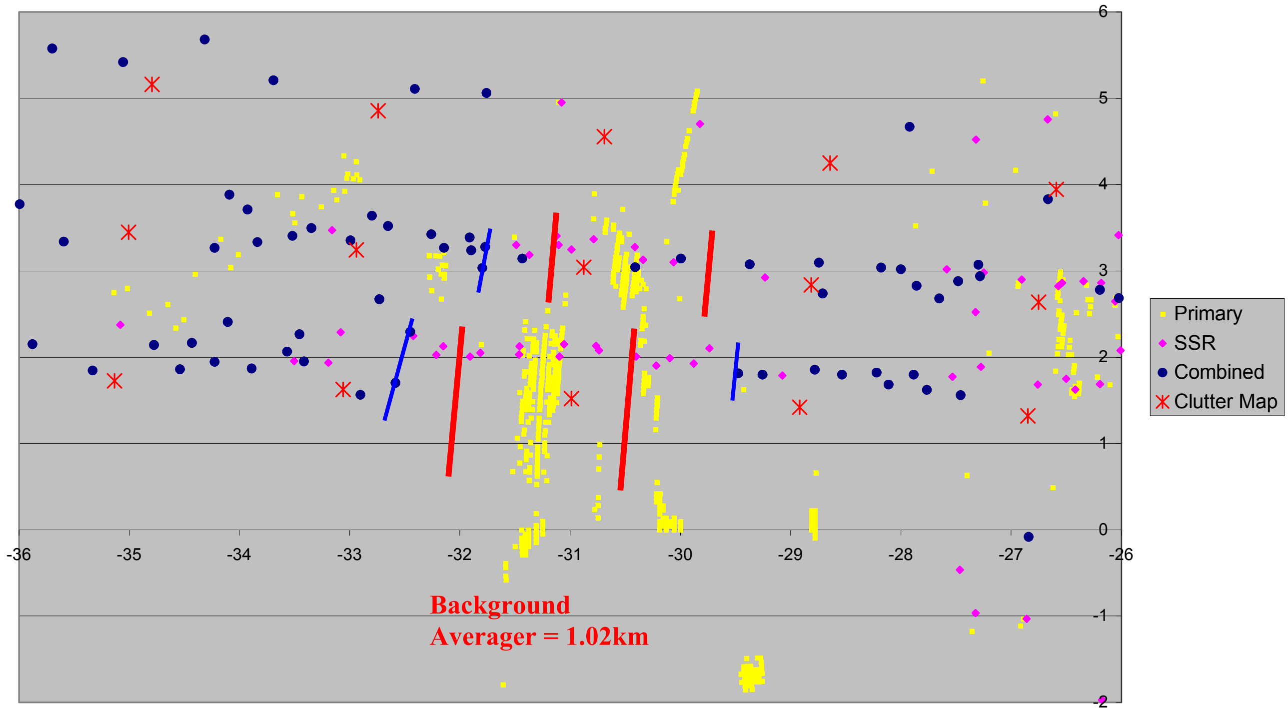


Figure 4 - T101 Radar Data - Tucano in Normal Radar (no turbines turning)

From a visual inspection of Figure 4, there is a significant disparity between the lateral limits of the Background Averager sliding window and the observed effect; the difference between the 2 ranges is almost 100%. It appears unlikely that the sliding window in the Background Averager is the sole source of reduced sensitivity.

7. <u>Additional Inputs to Background Averager</u>. From information provided by BAES Insyte, the 'In-Range' and 'Out-Range' sliding windows are not the only inputs to the Background Averager. The output of the Background Averager is based on the greatest of 4 inputs: 'In-Range' average over 1 km, 'Out-Range' average over 1 km, 'Gof Threshold' system parameter and 'Min Bgnd' system parameter. The sources of the 'Gof Threshold' and 'Min Bgnd' system parameters were not available to the Air C2 OEU and require further investigation. Based on the available data we were unable to conclude whether the loss of detection in the Normal Channel, outside of the Clutter Map ranges, was solely the result of the Background Averager in and out ranges (sliding window). It remains highly likely that the loss of detection is the result of processing within the Background Averager, particularly as no other clutter processing was being applied in this case.

OVERHEAD OBSCURATION – ALL ALTITUDES

8. Overhead Obscuration. During the previous AD Radar Trial obscuration in the Normal Radar channel was observed in all radar beams overhead the wind turbines. This was again observed during this latest Trial; the data used to compile Figure 2 was recorded during overflights at heights from surface to 23 000 ft AMSL. Overhead obscuration is now consistent with expectations for performance of the T101 and is believed to be related to the use of a single aloft Clutter Map for all of beams 2-7, as discussed at Annex D. There are 2 likely sources for loss of sensitivity in the aloft clutter map: wind turbine reflections in the main lobe of Beam 2 and wind turbine reflections in the first elevation side-lobe of the upper beams.

9. Beam 2 Main Lobe Performance. During this Trial, the range from the T101 to the P&L wind turbine farm was 35 miles. The radar antenna was at approximately 1500 ft and the top of the turbines was approximately 2000 ft. By simple calculation we can derive that the base of Beam 2 was approximately 3000 ft overhead the turbines. However, iaw convention these beamwidth figures are based on the 3dB (half power) point of the beam. The RCS of the wind turbines at P&L is such that 30 dB of attenuation is required before they are lost below the ambient noise level. Therefore, the 15 dB attenuation point of the main lobe is the lowest level of attenuation that will suppress the returns from the turbines.

10. Beam 2 Main Lobe at 15 dB Attenuation. From near-field range measurements provided by BAES Insyte it is possible to estimate the elevation beamwidths for the T101 at the 15 dB point; we can then derive that the base of Beam 2 is now approximately 800 ft below the wind turbines. In fact the wind turbines are in approximately the 10-12 dB point of Beam 2 and so are only being attenuated by 20-24dB by the 2-way Transmit/Receive path. This is insufficient to reduce the strength of the reflections from the wind turbines below the ambient noise level. Reflected energy from the P&L wind turbine farm will be entering the aloft clutter map through Beam 2 and raising the detection threshold for affected clutter cells within all of Beams 2-7; this effect will be the same in all 6 aloft beams. Beam 2 is assessed as the most likely source of reduced sensitivity in the upper beams of the T101 during this Trial.

11. Elevation Side-Lobes. Prior to BAES Insyte informing the Air C2 OEU of the changes to the beam structure of the T101 (making Beam 2 an aloft beam) the loss of sensitivity in the upper beams was believed to result from energy received in the elevation side-lobes of the upper beams. A key component of this Trial was the observation of the video returns in each of the individual beams as displayed at the Radar Management Console of the T101. Observations made during the Trial showed video returns corresponding to the P&L wind turbine farm in more than one of the upper beams. At the 15 dB point the base of each upper-beam main lobe is over 9000 ft above the tips of the wind turbines. The pattern of the beam recorded on the near-field range is such that the first null occurs at approximately 3000 ft above the tips of the wind turbines. The first elevation side-lobes of the most relevant upper beams encompass the elevation of the wind turbines at approximately 26 dB attenuation relative to the peak of the main lobe (one way transmit path). The phase shifters used to shape the T101 beams are set the same in both receive and transmit, giving the same beam shape and same levels of gain for both segments of the complete signal path. Therefore, the attenuation of returns from the wind turbines in the upper beams should be approximately 50 dB. There is no evidence to suggest that returns from the P&L wind turbines are of an order of magnitude greater than 30 dB over the ambient noise level. The observation of returns from the turbines in the video signal for the upper beams during this Trial was anomalous. The observation leads to the following possible conclusions:

a. Elevation Side-Lobe Performance. It is possible that the performance of the T101 antenna under test was not iaw the near-field range data provided by BAES Insyte. This may indicate an error in the original data collection methodology or a fault with the T101 under test that has developed since delivery. The only way to be certain of the elevation side-lobe performance is to measure the same System on a near-field range, ideally a different range to that first used.

b. Wind Turbine Farm RCS. The RCS of the P&L wind turbine farm has only been estimated based on established industry norms. However, measurements taken during a previous trial using an MoD ATC Watchman Radar (2.7-3.1 GHz) deployed to the same location as the T101 indicated that attenuation of 30 dB in the normal radar channel was sufficient to suppress all returns from the wind turbines. It is possible that errors arose during this measurement process; however, it is consistent with standard industry models.

12. Use of Electronic Tilt (E-Tilt). Further evidence was obtained by using the E-Tilt feature of the T101 to influence the beam elevation. With 3º of positive e-tilt applied, all the radar beams, measured at both the 3 dB (half-power) point and the 15 dB point are above the wind turbines. Full attenuation of the wind turbine returns is not expected to occur until the 15 dB point of the beams. With the T101 set-up in this configuration (+3.0º E-Tilt) there is no route for reflections from any of the wind turbines to enter the main lobes of any of the beams (Normal Radar or MTI). Despite the +3.0º E-Tilt, anomalous returns in the video display for the upper beams of the Normal Channel remained. These observations are consistent with returns being received through the first elevation side-lobe, but cannot be regarded as proof. Further evidence was obtained by increasing the E-Tilt to +5.75º; at this setting the video returns disappeared from the two uppermost beams, another result consistent with the elevation side-lobe theory. The only beam in which anomalous returns have not been seen is Beam 1. Beam 1 is the only Normal Radar channel processing clutter in its original design configuration with no input to its Clutter Map from any other beam. To further explore this problem, a Hawk T Mk1A was flown over the turbines at a variety of heights with +3.0º E-Tilt applied to the radar.

13. The radar plot at Figure 5 shows a Hawk T Mk1A flying over and behind the wind turbines at 6000 – 12 000 ft AMSL; at these heights the ac was operating in Beam 1 of the radar. The radar produces consistent combined plots with no apparent negative impact from the wind turbines, even though 101 of the 103 turbines were in motion during the sortie. The apparent physical position of the primary returns from the wind turbines has been shifted in space by approximately 1 km to the east.

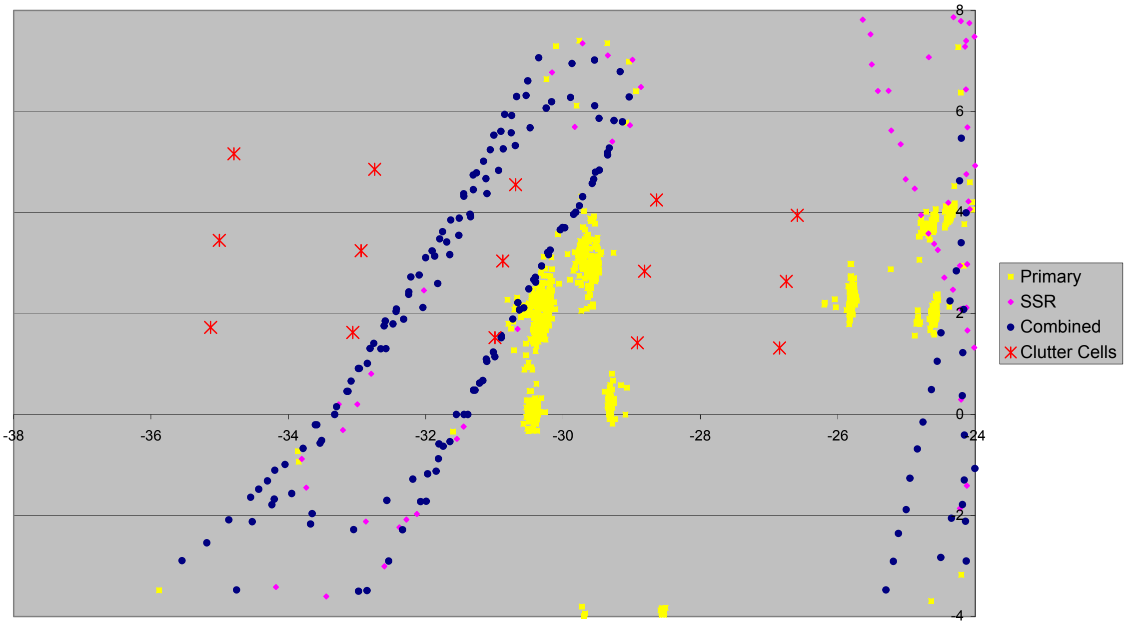


Figure 5 - T101 Radar Data (+3.0º E-Tilt) - Hawk T Mk1A

14. The result of plotting primary returns from Figure 5 as plot elevation (based on primary radar height) against range from the radar are shown at Figure 6:

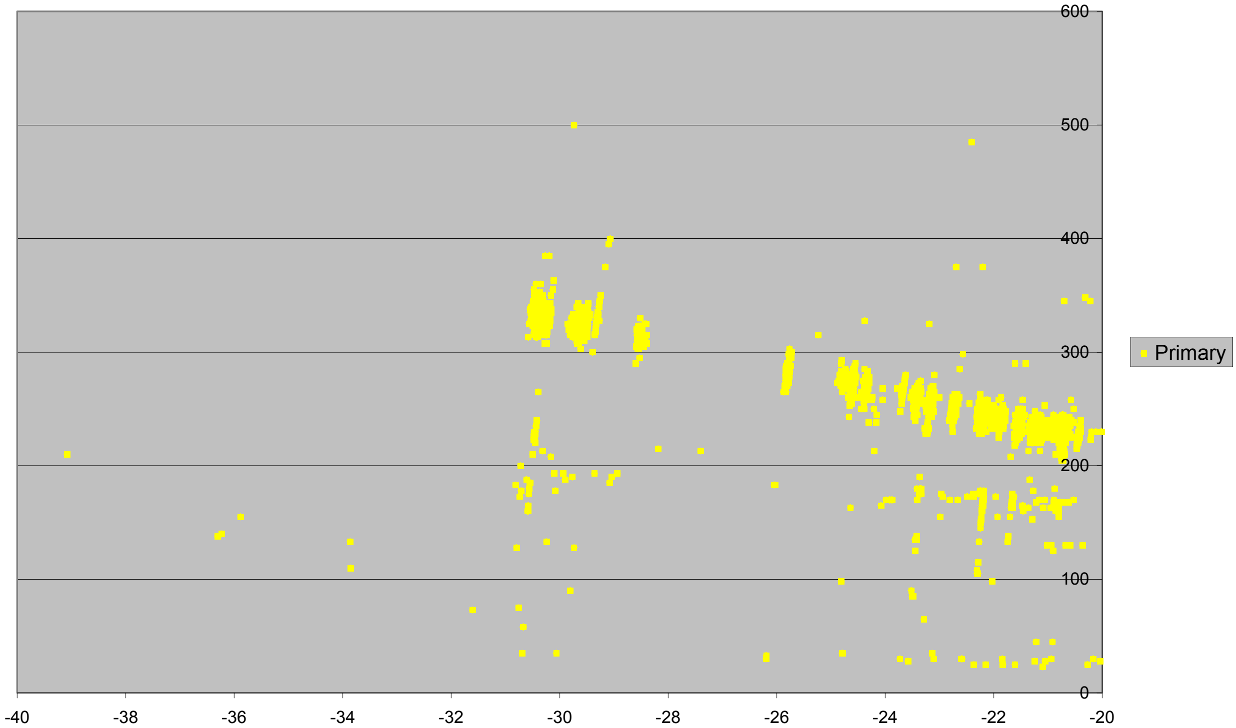


Figure 6 - T101 Radar Data - Primary Returns (Height in Flight Levels v Range)

All the primary returns from the wind turbines are appearing in upper beams, with no impact in the lower beams. The plan position error for the wind turbines was occurring due to a faulty calculation of slant range based on a ground tgt appearing, incorrectly, to have a primary height of over 32 000 ft.

15. By re-plotting the data with the slant range correction removed from the primary returns the radar plot at Figure 7 is obtained:

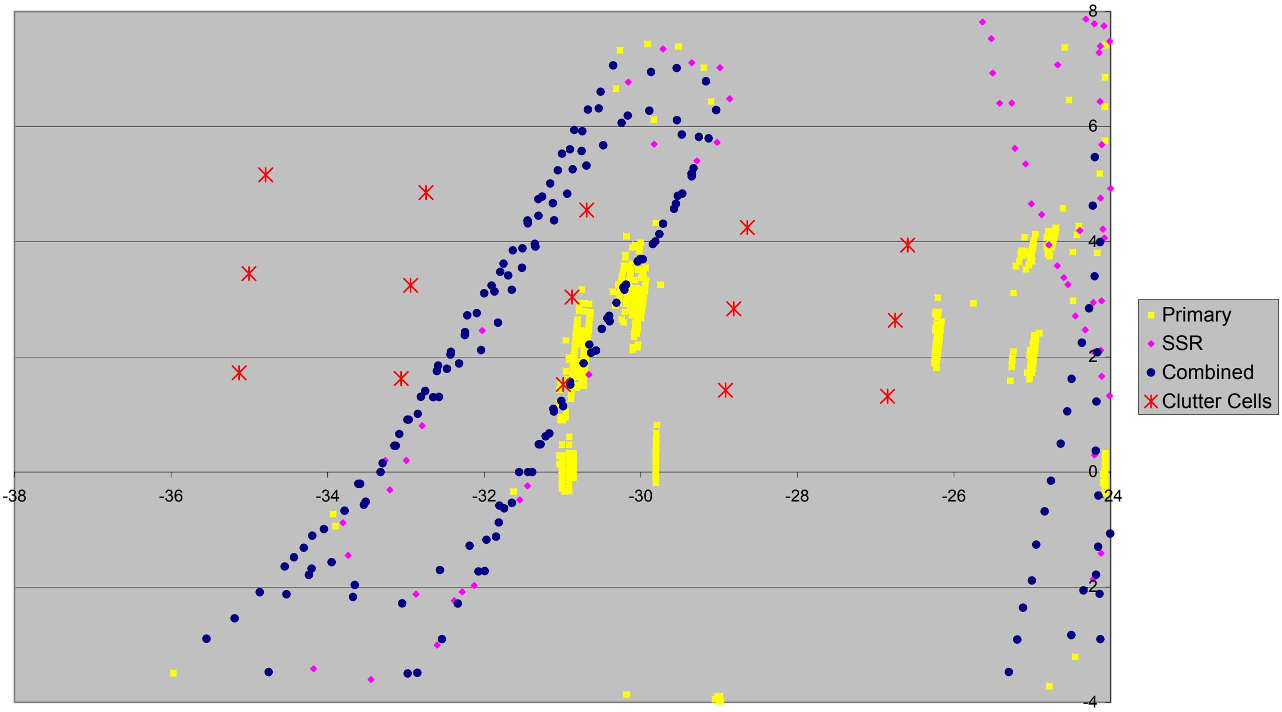


Figure 7 - T101 Radar Data (+3.0º E-Tilt) no slant range on primary - Hawk T Mk1A

This display is consistent with expectations and supports the following conclusions:

a. Returns from the P&L wind turbine farm were being observed in the Upper Beams of the T101 Radar deployed at Clee Hill, most likely through the elevation side-lobes.

b. Where a radar beam and its side-lobes was focused over, but not on, a wind turbine farm then consistent detection of low RCS ac, such as the Hawk T Mk1A was possible.

16. The above data only considers the case for Beam 1, that being the only beam with a unique Clutter Map. The same profile, with the same radar settings, was repeated with the ac at 18 500 ft AMSL; this places the ac in Beam 2. The results are shown at Figure 8.

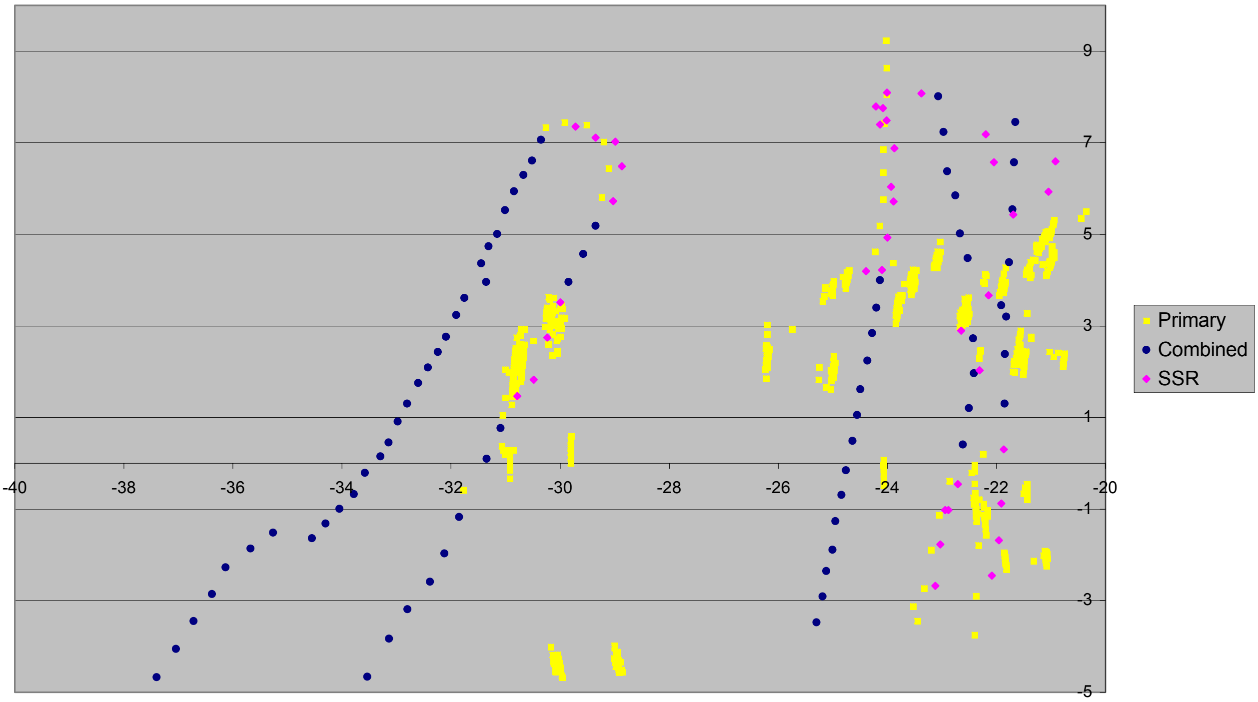


Figure 8 - T101 Radar Data (+3.0º E-Tilt) - Hawk T Mk1A in Beam 2

Even though Beam 2 has no main-lobe line of sight on the wind turbines there is still loss of detection over the wind farm. As shown at Figure 6, the only returns from the wind turbines are in upper beams. The effect of a composite Clutter Map for all of Beams 2-7 allows the reflections received in the upper beams to effect all of Beams 2-7. The previous statement can be redefined as follows:

> *Where a radar beam and its side-lobes are focused over, but not on, a wind turbine farm then consistent detection of low RCS ac, such as the Hawk T Mk1A is possible*, only if shared clutter processing techniques are not affected by detections in other beams.

<u>LOSS OF DETECTION IN MTI RADAR CHANNEL</u>

17. <u>Evidence</u>. Following the previous AD Radar Trial, the following hypothesis was formed:

> H_0 – Loss of detection in the MTI channel in the vicinity of wind turbines is due to the action of the Background Averager.

Graphical illustration of the loss of detection in the MTI channel is less obvious than the corresponding output for the Normal Radar Channel. Figure 9 shows data collected with the Normal Radar channel removed by application of 84 dB attenuation. The majority of the 103 turbines were turning during data collection.

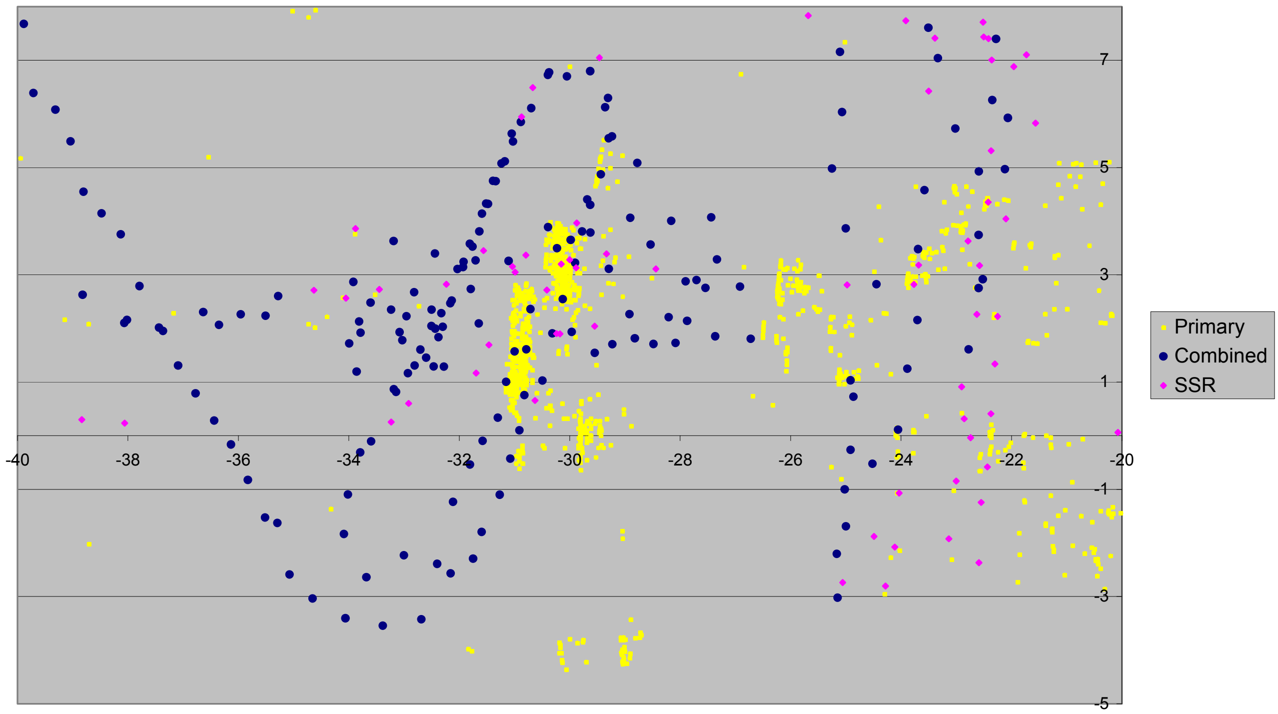
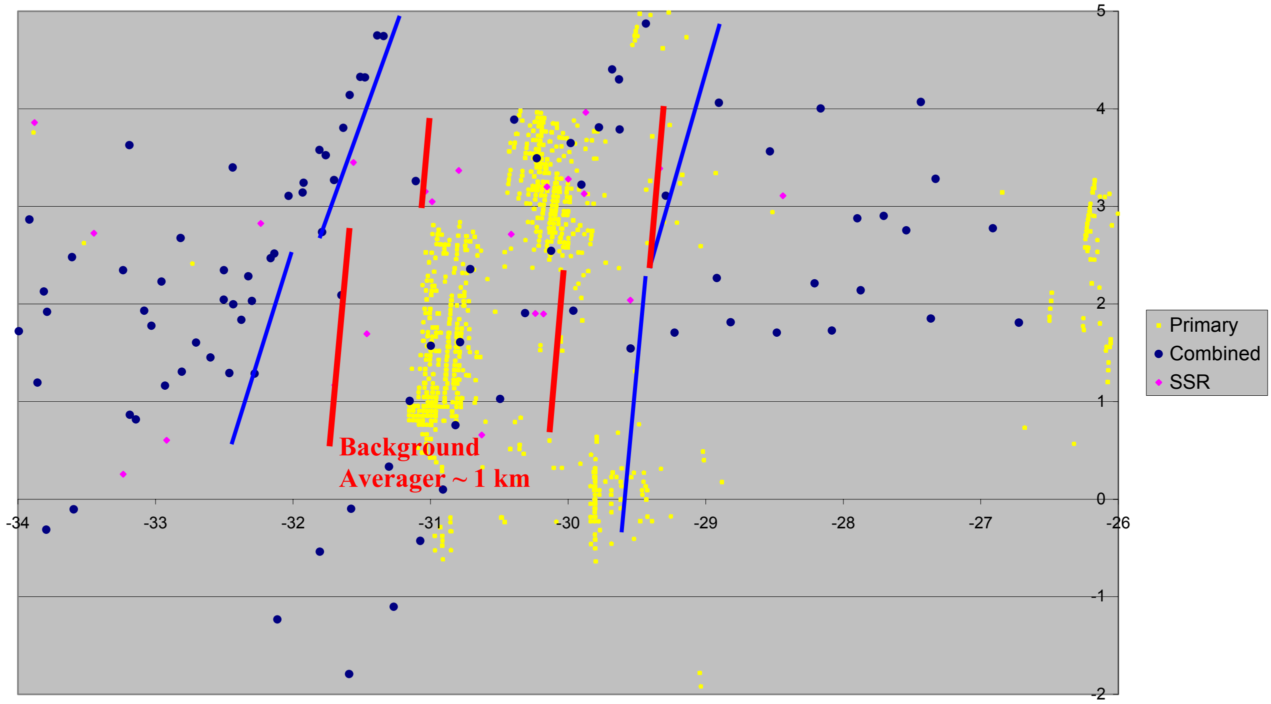


Figure 9 - T101 Radar Data - MTI Radar

18. Even with a smaller data sample size it is apparent that the division between regions of good and poor detection are less defined than they were in Normal Radar. At Figure 10, below,



the region around the Wind Turbine Farm is enlarged.

Figure 10 - T101 Radar Data - MTI Radar

19. To provide evidence in support of this hypothesis without access to processor level information it was necessary to record the lateral bounds of the observed effect and compare this data to the known parameters of the Background Averager. The red and blue overlays on Figure 10 represent the range of effect for the Background Averager and the observed range beyond which PD returns to normal, respectively. The correlation in the data is insufficient to prove our hypothesis but it does provide supporting evidence. A noise spike in the Background Averager will only occur if one of the cells of interest is occupied by a significant noise source; for the MTI channel and wind turbines this will be dependent on a concurrence of antenna rotation and blade rotation. The effect of wind turbines in the Background Averager will not be consistent sweep to sweep. As the Background Averager is operating over approximately 1km and producing an average figure for background noise the extent of attenuation in the tgt cell will vary with every sweep. This intermittent effect complicates data analysis.

20. To increase the sample size under evaluation, additional data collected from the Normal Radar channel with the Clutter Map removed was added. The Clutter Map was removed by setting both the ground and aloft clutter ranges to 8 nm.

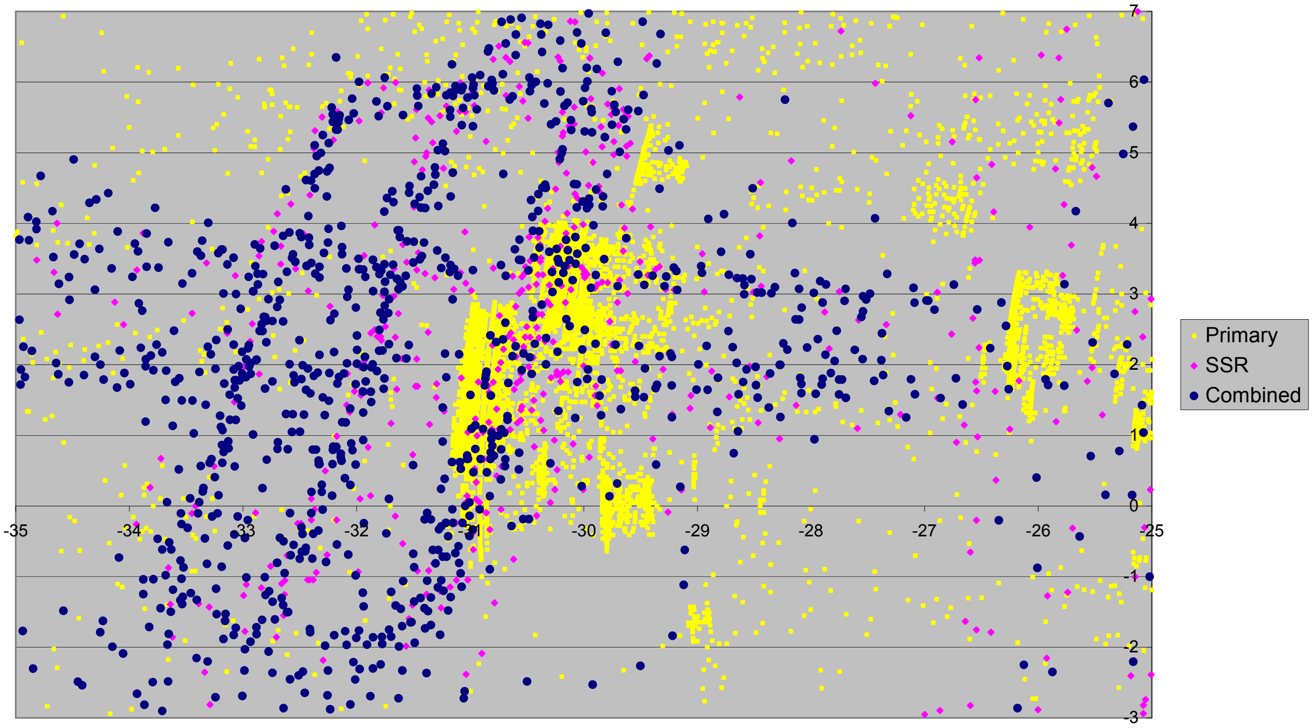


Figure 11 - T101 Radar Data - MTI Radar and Normal Radar (No Clutter Map)

At Figure 11 the sample size is considerably increased but the results remain ambiguous due to the intermittent nature of the interference from the rotating turbine blades.

21. At Figure 12 the area around the wind turbines is enlarged:

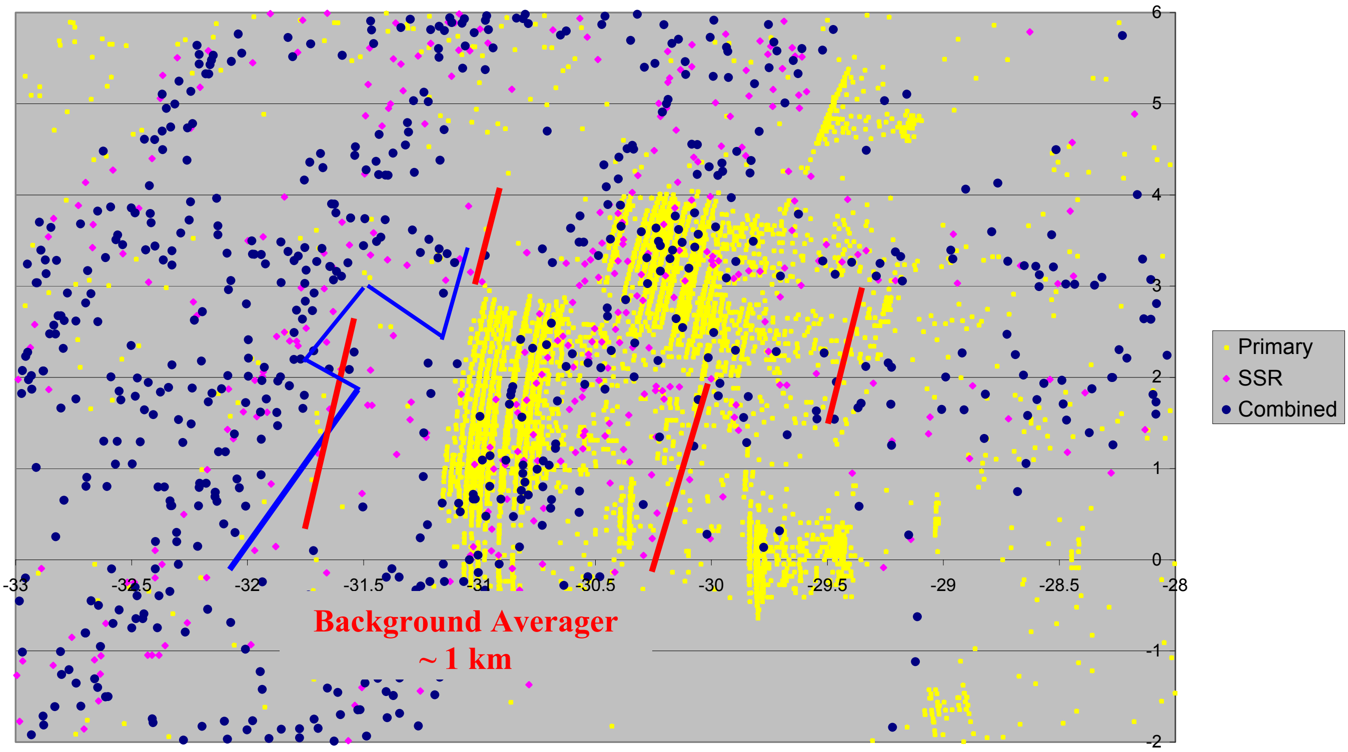


Figure 12 - T101 Radar Data - MTI Radar and Normal Radar (No Clutter Map)

The data remains more ambiguous than that collected in the Normal Radar channel with Clutter Maps in place. However, the following observations can be made:

a. Detection of ac in the MTI channel was consistent at ranges greater than 0.7 nm behind the wind turbines and was broadly in line with the predicted range of the Background Averager.

b. PD for ac in the MTI channel was intermittent in front of and overhead the wind turbines.

Therefore, the reduced sensitivity of the MTI channel behind the wind turbines appears to be bounded at a range that is consistent with the Background Averager (up to 1 km from the tgt cell). However, the actions of the Background Averager should be equal both in front of and behind the wind turbines. It is not possible to conclude that the loss of detection in the MTI channel is solely the result of the Background Averager sliding window although it remains likely that the window is influencing the sensitivity of the radar.

22. Additional Evidence – Turbines Not Turning. Having failed to establish that the Background Averager sliding window was causing the loss of sensitivity in the MTI Channel it was necessary to consider additional evidence. PD in the MTI Channel was not affected when no turbines are turning. As shown at Figure 13; the Hawk T Mk1A produced consistent combined plots overhead and in the vicinity of the wind turbine farm at all heights from 23 000 to 2000 ft AMSL. Therefore, loss of sensitivity in the MTI Channel was due to the motion of the turbines not physical obstruction of the beam. This statement appears obvious but is important as it discounts the possibility that the diffraction effect in the shadow of the physical turbine structure was disrupting detections in the MTI Channel.

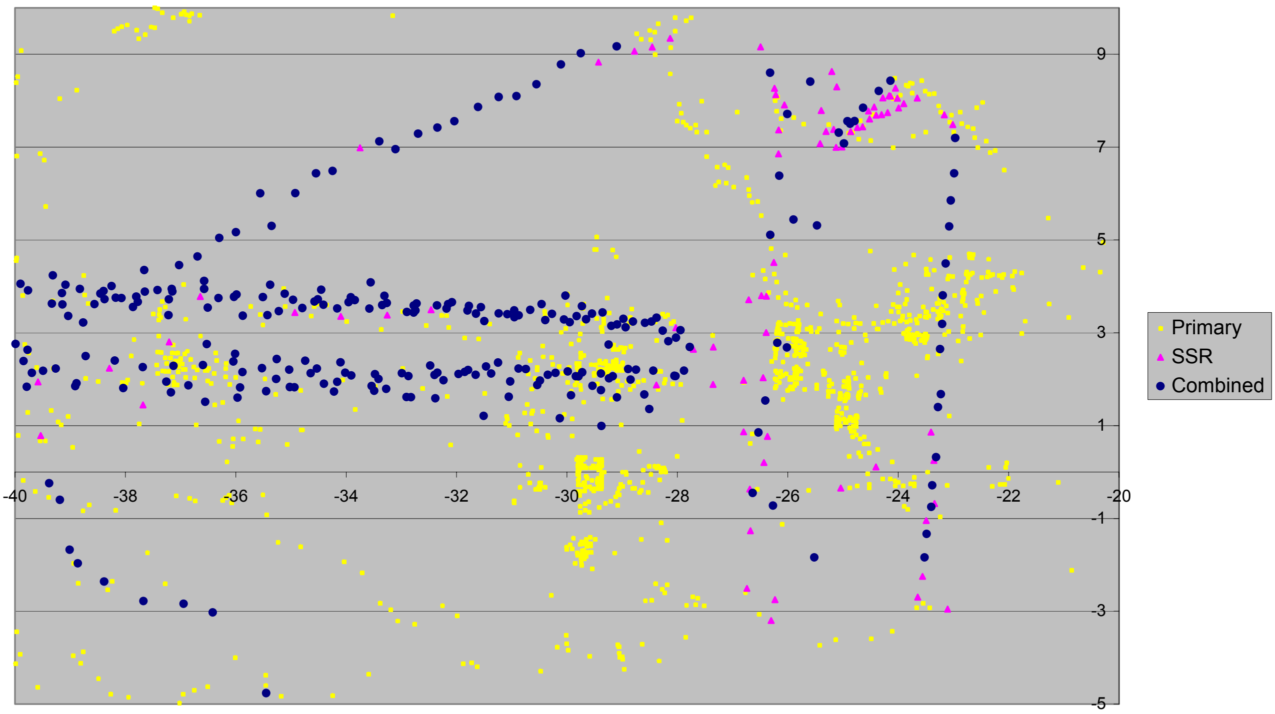


Figure 13 - T101 Radar Data – Hawk T Mk1A (No Turbines Turning)

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T101 BACKGROUND AVERAGER AND CLUTTER MAPS

BACKGROUND AVERAGER

1. System Description. The Background Averager in the T101 operates in both Normal and MTI Radar Channels. The actions of the sliding window within the Background Averager are performed every sweep and are independent for each beam. For an effect to influence radar processing of a wanted tgt through the Background Averager it must be present in the same beam as the tgt and on the same sweep. The average noise level is calculated approximately 1 km either side of the tgt cell. This produces 2 separate values for background average, one in front of and one behind the tgt cell (relative to the radar); only the greater of these 2 values is used thereafter. An additional guard cell either side of the tgt cell is omitted from the calculation to prevent contamination of the background noise calculation by wanted tgt reflections. A large radar reflector such as a wind turbine would significantly raise the background average in a tgt cell at ranges up to 1 km, measured on a radial from the radar.

2. Overall Effect. The practical effect of the Background Averager on tgt detections is to create a region 1 km either side of a wind farm within which radar sensitivity is significantly reduced as illustrated below:

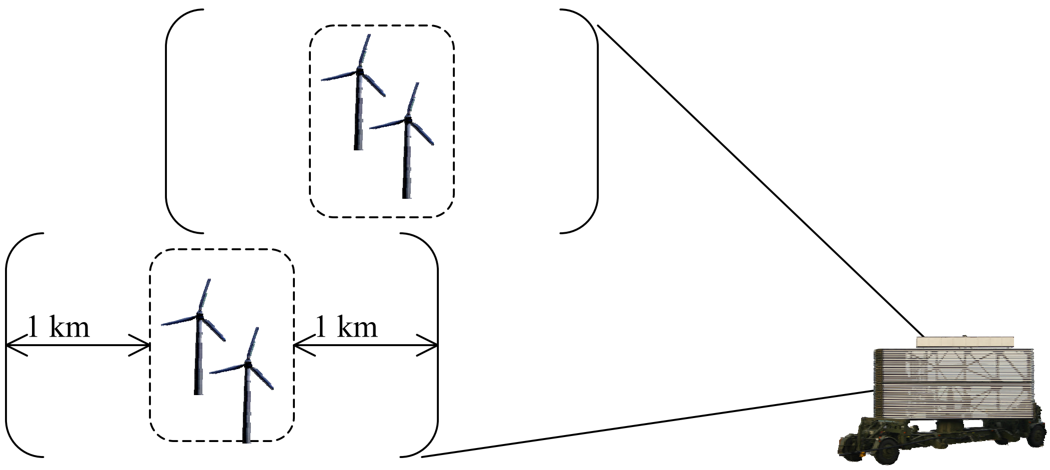

Figure 14 - T101 Reduced Sensitivity Around Wind Turbines due to Background Averager

3. System Parameters. In addition to sampling the sliding windows, the Background Averager also considers the value of 2 system parameters (‘Gof Threshold’ and ‘Min Bgnd’). Detailed information on this processing was not available to the Air C2 OEU and is beyond the scope of this report.

CLUTTER MAPS

4. To process clutter resulting from environmental detections within the Normal Radar (non-MTI) channel, the processor compiles a map. Unlike the Background Averager which operates instantaneously, sweep by sweep, the Clutter Map is compiled slowly over a number of sweeps. In simple terms, the clutter threshold held within each cell of the Clutter Map is changed by less than 1dB each sweep unless the clutter threshold is of the same amplitude as the strongest clutter return within the cell. For the T101, each clutter cell is considerably larger than the minimum resolution cell of the radar. Each clutter cell is divided into multiple radar range resolution cells. When evaluating the clutter threshold for a given clutter cell, equal weight is given to each of the range resolution cells contained within it. If a large reflector, such as a wind turbine, is present in any one of the sub-cells then the clutter threshold for the entire clutter cell will be raised to an equivalent amplitude (in increments). The practical effect of this process is to allow a single noise source to significantly degrade radar sensitivity within a large clutter cell.

5. The Clutter Map structure within the T101 is divided into 2 regions, aloft and ground. When the radar was designed the ground Clutter Map encompassed Beams 1 and 2, the aloft Clutter Map encompassed Beams 3-7. The processing of Beam 2 was altered by BAES Insyte due to problems encountered in high clutter environments. Beam 2 is now processed as an aloft clutter map although it uses the Ground Clutter Range to determine the range at which it is employed. Beam 1 stands alone as a ground Clutter Map and detections in Beam 1 have no impact on the rest of the radar beams. The combination of Beams 2-7 into a single aloft Clutter Map cause detections in any one of the beams to equally affect the sensitivity of the other aloft beams.

ANNEX E
DATED 12 AUG 05

GUIDANCE ON MITIGATION OF THE INTERFERENCE EFFECTS BETWEEN WIND TURBINES AND AD RADARS

1. Introduction. The Trial Report for the previous AD Radar Trial included discussion of potential solutions to mitigate the interference effects of wind turbines on AD Radars. The technical understanding within the Air C2 OEU has been considerably enhanced since the completion of the previous AD Radar Trial and significant additional evidence gathered during this Trial. It is necessary to re-examine potential solutions to the interference effects of wind turbines on AD Radar.

2. Situation. The interference effects of wind turbines on AD Radar can be categorized as follows:

a. Overhead Obscuration. During both the previous AD Radar Trial and this Trial, loss of detection of wanted tgts occurred directly over and in the immediate vicinity of wind turbines. In extreme cases, this obscuration occurred at all levels.

b. False Alarms. One of the earliest recorded interference effects from wind turbines was observation of false alarms, predominantly resulting from the motion of the turbines inducing a Doppler shift in the reflected energy and inducing the radar processor to treat the return as though it were from an ac. This problem is further exacerbated if multiple returns within a wind farm induce the associated track production system to initiate and update a false track on the false alarms.

c. Shadow. It has long been believed that the diffraction effect of the physical obstruction of the radar energy by the turbine structure causes a loss of sensitivity behind the turbines. This remains unproven by either the previous AD Radar Trial or this Trial. However, we were unable to discount it.

3. Potential Solutions. Many different methods for mitigating the effects of wind turbines on radars have been suggested. The key options of relevance to the UK AD Radar system are: improved clutter processing; optimised Background Averager; optimised 3-D beam patterns; additional sensors and reduced turbine RCS (stealth turbines).

4. Clutter Processing. To minimise the effect of wind turbines on radar there are 2 key considerations for the Clutter Map processing:

a. Fine Clutter Maps. The clutter cells in the T101 are regarded as coarse; they comprise multiple radar resolution cells. Therefore, large clutter sources such as wind turbine farms can raise the threshold in an area considerably greater than their geographical footprint. The use of fine clutter cells that correspond in dimension to the radar resolution cells could reduce the area of effect. Provided the turbine spacing (tip to tip) was equal to or greater than 3 clutter cells (in both azimuth and range) then the system should detect tgts between turbines. Fine clutter maps will not remove the problem of wind turbine interference but by reducing the area of effect they represent a significant mitigation technique.

b. Independent Clutter Maps. Another feature that has been shown to impact on the interference of wind turbines on radar is the use of composite clutter maps. The T101 uses 2 clutter maps, a ground clutter map for Beam 1 and an aloft clutter map for Beams 2-7. The use of composite clutter maps allows interference received in one beam to affect every other beam sharing the same map. For the T101, this feature manifests in 2 ways:

(1) The attenuation of Beam 2 at 0º elevation is approximately –12 dB. Therefore, a significant signal strength reflected from the wind turbines is able to populate the aloft clutter map through the main lobe of Beam 2.

(2) A large body of empirical evidence collected during the previous AD Radar Trial and this Trial indicates that reflected energy from the wind turbines is entering the upper beams of the T101 Radar. This is most likely occurring through the first elevation side-lobe. It is not yet possible to confirm this theory.

The clutter processing observations made during this Trial are necessarily T101-specific. Where principles of radar processing have been discussed, such as the impact of coarse clutter and composite maps, those principles are applicable for any modern radar system. To mitigate the interference effects of wind turbines on AD Radars, clutter processing systems should employ independent clutter maps with the finest achievable clutter cell resolution.

5. Optimised Background Averager. The effects of the Background Averager during this Trial were harder to quantify than those of the Clutter Maps. There is little doubt that the presence of large reflectors (the wind turbines) in the range covered by the Background Averager has a significant impact on overall PD. Measures designed to optimise the Background Averager for an environment populated by a low density of extremely large RCS objects would be of significant benefit. Most radars employ background-averaging techniques that were intended to mitigate the effect of ground clutter and environmental factors. These natural phenomena tend to have a smoother profile than artificial clutter induced by wind turbines. Wind turbines represent a large RCS object occupying a small geographical area. Due to the magnitude of their RCS the impact of individual turbines on the Background Averager is disproportionate. Technical details of methods to optimise the Background Averager are beyond the scope of this report and are system dependent. Methods to reduce the impact of geographically small features with large RCS would have benefit in increasing the sensitivity of radars in the vicinity of wind turbines.

6. Optimised 3-D Beam Patterns. Empirical data analysis during this Trial demonstrated that reflections from the wind turbines are detected in the upper beams of the T101 even though they are not within the main lobe. The T101 processor cannot distinguish between extremely large returns in the elevation side-lobes and small returns in the edges of the main lobe, although some other AD Radar systems employ side-lobe cancelling techniques. During this Trial, the consistent observation of video returns from the turbines in the upper beams of the T101 was highly anomalous. It has been suggested that the beam structure of the T101 under test be re-evaluated. In the absence of any other symptoms there is no evidence to suggest that the beam forming is not performing to specification. We are forced to conclude that there is an interaction between beam shape and the interference effects of wind turbines. Further investigation during this Trial also demonstrated that where an individual beam has a null (in both transmit and receive beams) at the elevation of the wind turbines, there is no interference from the wind turbines and detection of low RCS tgts is consistent at all altitudes. During this Trial this was achieved through the use of the E-Tilt feature of the T101. This allows us to deduce that a correctly shaped beam, with a null over the entire region of the wind turbines, would suffer no interference effects from the turbines. The most efficient way to support null-steering in an AD

Radar is the use of an active phased array antenna. To reduce costs it may be more efficient to employ a small active phased array, possibly a single non-rotating antenna assembly, to gap-fill overhead and in the vicinity of known wind turbines. Active phased array technology offers a potential mitigation technique for the interference effects of wind turbines on AD Radar, particularly as a localised gap-filler. It is also possible that existing passive phased array radars could be modified to support adaptive null steering but this is likely to be both complex and expensive.

7. <u>Stealth Turbines</u>. The interference effect of wind turbines on radar is rooted in the extremely large RCS of modern wind turbines. The relatively small turbines observed during this Trial are believed to have an RCS of approximately 300 m^2. Large turbines proposed for UK offshore developments are estimated to have an RCS of at least 10 000 m^2. During this Trial, we demonstrated that an increase in tgt ac RCS of 10-20 dB[19] could be sufficient to allow detection in conditions where it had previously not been possible. For the trial, this was achieved through the use of different ac types and different ac aspects relative to the radar. Ac RCS increase is not a practical solution, as we have no control over the RCS of potential hostile ac. A decrease in the RCS of the turbines would have the same effect as an increase in the RCS of the ac. Any reduction in the RCS of the turbines can only be of benefit in mitigating their effect on radar. It is unlikely that the RCS of a turbine could ever be reduced sufficiently to represent a single solution to the problem. As part of a composite solution along with other techniques discussed here it is likely that stealth turbines offer significant potential.

8. <u>Additional Sensors</u>. The use of additional sensors as a mitigation technique is interwoven with all other mitigation techniques and hence needs to be considered last. Given that the most significant interference effect of wind turbines on AD Radar is the overhead obscuration, geographical sensor diversity is insufficient to mitigate the problem. Many of the potential technological solutions to the problem will incur a cost either in terms of modifications to existing sensors or potentially expensive stipulations for the design of future sensors. It may be more economic to deploy an additional sensor, employing the technologies discussed above, to fill in the gap left by interference in conventional sensors. This is particularly pertinent when considering the use of an active phased array surveillance radar. The most significant cost of an active phased array surveillance radar is the antenna elements and 2 significant technological challenges are antenna rotation and antenna cooling. If the only requirement is to gap-fill over a static wind turbine farm it may be possible to deploy a single face, non-rotating, antenna staring over the area of interest. Electronic beam steering across a single planar active phased array allows 120º of coverage, notwithstanding the loss of sensitivity towards the edges of the arc. Even the large wind farms proposed for off-shore development within the UK are well within the maximum range coverage of a long range air surveillance radar and so loss of sensitivity at the edges of arc is not likely to be a significant constraint.

[19] 10 – 100 times.