International Energy Agency R&D Wind

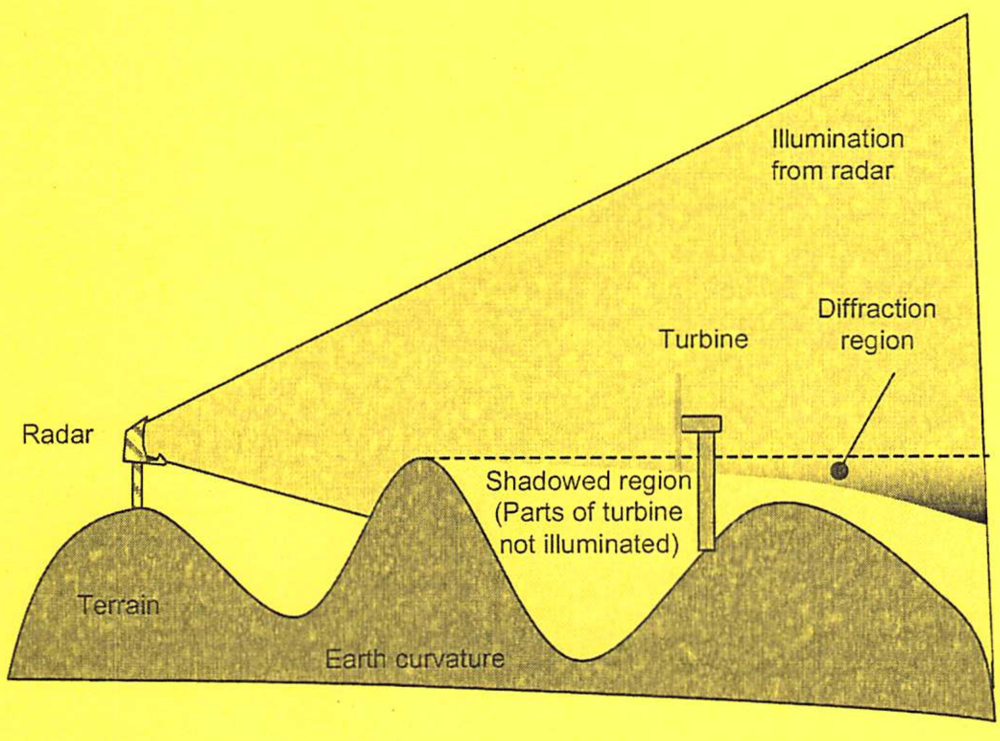
INTERNATIONAL ENERGY AGENCY

Implementing Agreement for Co-operation in the Research and Development of Wind Turbine Systems ANNEX XI

45th IEA Topical Expert Meeting

Radar, Radio Links and Wind Turbine Systems

London, UK, March 2005
Organised by: DTI



VATTENFALL

Scientific Co-ordination:
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International Energy Agency R&D Wind

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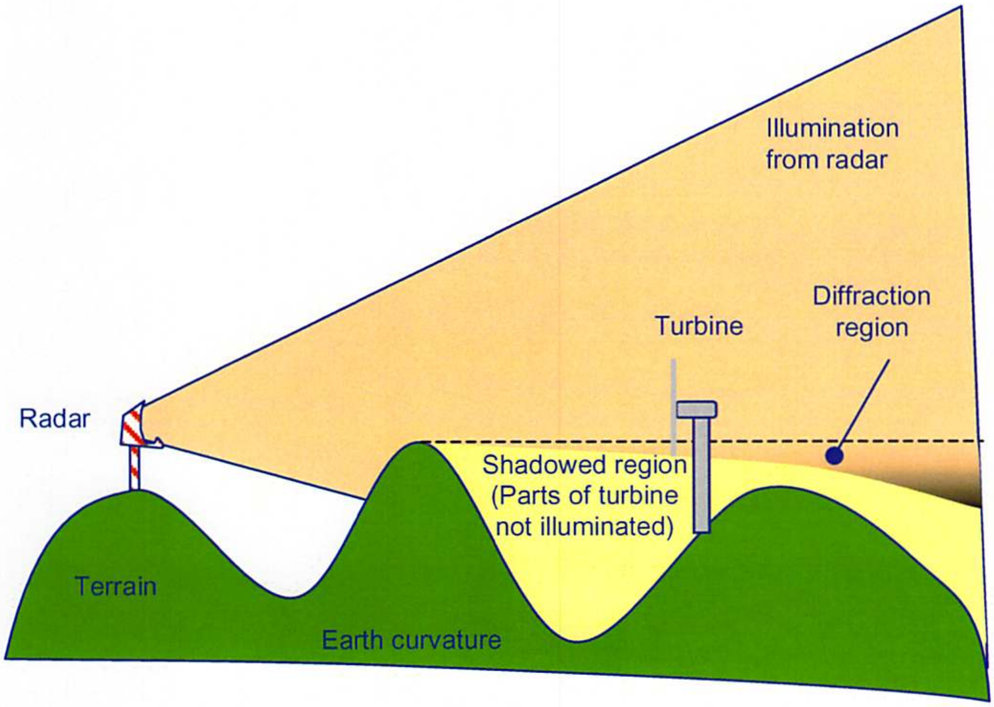

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IEA R&D Wind

IEA Topical Expert Meeting #45

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International Energy Agency R&D Wind

ANNEX XI
BASE TECHNOLOGY INFORMATION EXCHANGE

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The objective of this Task is to promote wind turbine technology through cooperative activities and information exchange on R&D topics of common interest. These cooperative activities have been part of the Agreement since 1978.

The task includes two subtasks. The objective of the first subtask is to develop recommended practices for wind turbine testing and evaluation by assembling an Experts Group for each topic needing recommended practices. For example, the Experts Group on wind speed measurements published the document titled "Wind Speed Measurement and Use of Cup Anemometry".

The objective of the second subtask is to conduct joint actions in research areas identified by the IEA R&D Wind Executive Committee. The Executive Committee designates Joint Actions in research areas of current interest, which requires an exchange of information. So far, Joint Actions have been initiated in *Aerodynamics of Wind Turbines, Wind Turbine Fatigue, Wind Characteristics, Offshore Wind Systems and Wind Forecasting Techniques.* Symposia and conferences have been held on designated topics in each of these areas.

In addition to Joint Action symposia, Topical Expert Meetings are arranged once or twice a year on topics decided by the IEA R&D Wind Executive Committee. One such Expert Meeting gave background information for preparing the following strategy paper "Long-Term Research and Development Needs for Wind Energy for the Time Frame 2000 to 2020". This document can be downloaded from source 1 below.

Since these activities were initiated in 1978, more than 60 volumes of proceedings have been published. In the series of Recommended Practices 11 documents were published and five of these have revised editions.

All documents produced under Task XI and published by the Operating Agent are available to citizens of member countries from the Operating Agent, and from representatives of countries participating in Task XI.

More information can be obtained from:

1. www.ieawind.org
2. www.windenergy.foi.se/IEA_Annex_XI/ieaannex.html

IEA R&D Wind - List of Topical Expert Meetings

For more informatiuon visit http://www.windenergy.foi.se/ and click on IEA
Documents can be obtained from Sven-Erik Thor at sven.erik.thor@vattenfall.com

Nr	Title	Date	Year	Location	Country
44	System Integration of Wind Turbines	November	2004	Dublin	Ireland
43	Critical Issues Regarding offshore Technology and Deployment	March	2004	Stockholm	Sweden
42	Acceptability in Implementation of Wind Turbines in Social Landscapes	March	2004	Kolding	Denmark
41	Integration of Wind and Hydropower Systems	November	2003	Portland	USA
40	Environmental issues of offshore wind farms	September	2002	Husum	Germany
39	Power Performance of Small Wind Turbines not connected to the Grid	April	2002	Soria, CIEMAT	Spain
38	Material Recycling and Life Cycle Analysis (LCA)	March	2002	Risø	Denmark
37	Structural Reliability of Wind Turbines	November	2001	Risø	Denmark
36	Large Scale Integration	November	2001	Newcastle	UK
35	Long term R&D needs for wind energy. For the time frame 2000 – 2020	March	2001	Petten	the Netherlands
34	Noise Immission	November	2000	Stockholm	Sweden
33	Wind Forecasting Techniques	April	2000	Boulder	Usa
32	Wind energy under cold climtes	March	1999	Helsinki	Finland
31	State of the art on Wind Resource Estimation	October	1998	Lyngby	Denmark
30	Power Performance Assessments	December	1997	Athens	Greece
29	Aero-acoustic Noise of Wind Turbines	March	1997	Milano	Italy
28	State of the art of aeroelastic codes for wind turbines	April	1996	Lyngby	Denmark
27	Current R&D needs in wind energy technology	September	1995	Utrecht.	Netherlands
26	Lightning protection of wind turbine generator systems and EMC problems in the associated control systems	March	1994	Milan	Italy
25	Increased loads in wind power stations (wind farms)	May	1993	Gotherburg	Sweden
24	Wind conditions for wind turbine design	April	1993	Risø	Denmark
23	Fatigue of wind turbines, full-scale blade testing and non-destructive testing	October	1992	Golden, Colorado	USA
22	Effects of environment on wind turbine safety and performance	June	1992	Wilhelmshaven	Germany
21	Electrical systems for wind turbines with constant or variable speed	October	1991	Gothenburg	Sweden
20	Wind characteristics of relevance for wind turbine design	March	1991	Stockholm	Sweden
19	Wind turbine control systems-strategy and problems	May	1990	London	England
18	Noise generating mechanisms for wind turbines	November	1989	Petten	Netherlands
17	Integrating wind turbines into utility power systems	April	1989	Herndon	USA
16	Requirements for safety systems for LS WECS	October	1988	Rome	Italy
15	General planning and environmental issues of LS WECS installations	December	1987	Hamburg	Germany
14	Modelleing of atmospheric turbulence for use in WECS rotor loading calculations	December	1985	Stockholm	Sweden
13	Economic aspects of wind turbines	May	1985	Petten	Netherlands
12	Aerodynamic calculation methods for WECS	October	1984	Copenhagen	Denmark
11	General environmental aspects	May	1984	Munich	Germany
10	Utility and operational experience from major wind installations	October	1983	Palo Alto	California
9	Structural design criteria for LS WECS	March	1983	Greenford	UK
8	Safety assurance and quality control of LS WECS during assembly, erection and acceptance testing	May	1982	Stockholm	Sweden
7	Costing of wind turbines	November	1981	Copenhagen	Denmark
6	Realibility and maintenance problems of LS WECS	April	1981	Aalborg	Denmark
5	Environmental and safety aspects of the present LS WECS	September	1980	Munich	Germany
4	Rotor blade technology with special respct to fatigue design	April	1980	Stockholm	Sweden
3	Data acquisition and analysis för LS WECS	September	1979	Blowing Rock	USA
2	Control of LS WECS and adaption of wind electricity to the network	April	1979	Copenhagen	Denmark
1	Seminar on structural dynamics	October	1978	Munich	Germay

INTRODUCTORY NOTE
IEA Topical Expert Meeting #45
on
Radar, Radio, Radio Links and Wind Turbines

Mark Dorrington, Future Energy Solutions

1. CONTEXT FOR MEETING

Wind power is now a viable and well-established source of electricity generation, creating no harmful emissions and playing a major role in meeting policy targets for renewable energy generation over the next decade and beyond. The global strength of the wind energy sector has built continuously over the last decade, achieving annual growth of the order of 30%, indeed during 2003 the world's generating capacity grew by more than 8.3 gigawatts to a total of around 40 GW by the close of the year. The value of the global market for wind turbines was estimated at over 7 million U.S. Dollars. Of this world capacity, a full 90% is installed in the countries that participate in the IEA R&D Wind agreement.

National Statistics of the IEA R&D Wind member countries

IEA Annual Report 2003

Country	Total installed capacity	Offshore installed capacity	New installed capacity in 2003	Total No of turbines	Average new turbine size	Wind generated electricity	2003 National electricity demand	Typical wind system costs	Price paid to wind generators
	MW	MW	MW		kW	GWhrs/yr	TWhrs/yr	USD/kW	USD/KWh
Australia	198.0	-	93.0	-	-	-	192*	-	-
Canada	317.0	-	85.0	423.0	682.0	724.0	590	1,161	0.054
Denmark	3,114.0	406.0	225.0	5,389.0	2,045.0	5,542.0	35.2	1,107	0.061
Finland	47.0	-	4.0	-	-	-	81*	-	-
Germany	14,609.0	-	2,608.0	15,387.0	1,552.0	26,000.0	476*	-	-
Greece	424.4	-	69.0	772.0	793.0	850.0	50	1,323	0.101
Ireland	190.0	-	51.7	-	-	-	24*	-	-
Italy	904.0	-	116.0	1,491.0	800.0	1,450.0	319.7	1,134	0.130
Japan	506.0	1.2	172.0	609.0	1,180.0	569.0	841.5	1,167	-
Mexico	2.2	-	-	8.0	-	5.0	179.4	-	-
Netherlands	905.0	-	227.0	1,612.0	1,621.0	1,610.0	110.0	1,410	-
New Zealand	36.9	-	0.5	57.0	-	-	39*	-	-
Norway	100.0	-	3.0	65.0	1,540.0	-	115.0	1,254	0.031
Portugal	288.6	-	94.8	352.0	1,900.0	720.0	50.2	1,260	0.101
Spain	6,202.0	-	1,323.0	-	840.0	11,370.0	234.8	1,179	0.079
Sweden	404.0	22.5	59.0	675.0	980.0	690.0	145.6	1,230	0.046
Switzerland	5.4	-	-	21.0	-	5.0	55.0	-	0.085
UK	647.6	63.8	95.6	1,057.0	1,648.0	-	397.0	-	0.120
United States	6,374.0	-	1,689.0	N/A	1,400.0	19,500.0	3,602*	1,000	0.045

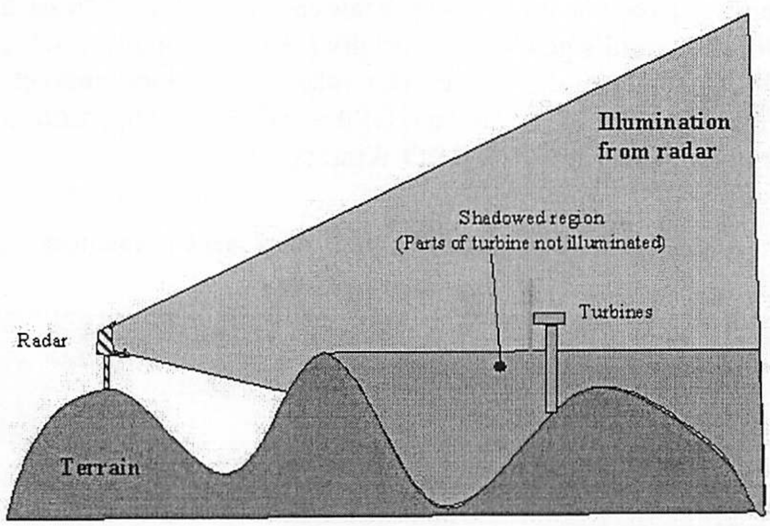
*2002 national electricity demand

- no available data

Increasingly, national policies are in favour of renewables, with wind energy able to take a leading role as an established and economic option. Wind energy is increasingly being viewed as mainstream, providing many benefits to new and existing markets. However, because of their physical size, in particularly their height, wind farms can have an effect on the aviation domain. Additionally, rotating wind turbine blades can have an impact on certain aviation operations, particularly those involving radar.

There are basically two ways in which the construction of a wind turbine or wind farm may impact upon aviation operations:

- The physical obstruction caused by a tall structure; and
- The effects that rotating turbine blades can have on a variety of navigational aids and other equipment.



General geometry of the problem- terrain shadowing

(or similar schematic demonstrating radar interference)

A major constraint on the deployment of wind energy is the restriction on siting turbines due to the potentially hazardous effects they may have on aviation and related defence interests. Objections have arisen over the potential effects on radar systems for both air traffic control and air defence and the impact on military low flying. The disturbance caused by wind turbines on various radar systems is not well understood and there is a lack of consensus on the severity of such effects. Nevertheless, major concerns have arisen within the aviation community regarding the potential for interference with radar systems and the subsequent effects on operations. However, the conflict between the two interests seems to be much less significant in some European countries where extensive wind energy developments exist.

One country where steps are being taken to address any potential conflict is the UK, where the Department of Trade and Industry (DTI) has set up a 'Wind Energy, Defence and Civil Aviation Interests Working Group' to investigate the issues of concern and improve understanding within both the aviation and wind energy industries. In parallel with this study, other work has been commissioned; specifically, scientific studies to improve understanding of the impacts of wind turbines on radar systems; and the creation of guidelines aimed primarily, but not exclusively, at wind energy developers, outlining the interactions between wind farms and aviation[1].

Interactions between wind turbines and aviation activity are potentially complex and in order to address this both operational and technical measures have been adopted. There is a lack of consensus on what the precise nature of the effects of wind turbines on radar actually are. Consequently, a number of studies are underway which will enlighten the current debate and provide some much-needed answers to key questions. Such studies encompass designing models to predict the impact of wind turbines on radar systems, and investigating the feasibility of mitigation measures which include 'Moving Target Indicator Processing', 'filters' and 'Non-Automatic Initiation'.

The aviation community worldwide has procedures in place which are designed to assess the potential effect of developments such as wind farms on its activities, and, where necessary to identify mitigating measures. Both wind energy and aviation are important to Global interests. Furthermore, defence remains one of the prime responsibilities of any Government. All communities involved in wind energy and aviation have legitimate interests that must be balanced to identify a way ahead that gives the best results, taking into account each countries overall national context. Neither aviation nor the wind industry is static and developments can be expected in both domains that may change the effects they have on each other.

Throughout Europe, and the world, Civil Aviation Authorities in individual nations are responsible for the oversight and regulation of all activities carried out by civil aviators and airport operators. Much of this is harmonised by the International Civil Aviation Organisation (ICAO)[2]. To achieve their aims, individual authorities conduct a wide variety of activities, including the licensing of aerodromes and air traffic service providers, the planning and regulation of airspace, including the communications, navigation and surveillance (CNS) infrastructure, and consultation with the military on the topic of airspace usage. The military in each country, predominantly (but not exclusively) in the form of air forces, needs access to airspace for primarily two purposes: training and national defence. This includes the surveillance of the airspace above and surrounding a country's territory, including over sea, the importance of which was highlighted by the events of 11 September 2001. It is therefore essential that the safety of aerodromes, aircraft and airspace is guaranteed and as wind turbines increase in size and number, their potential impact on aviation operations increases correspondingly.

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[1] 'Wind Energy and Aviation Interests – Interim Guidelines' (ETSU W/14/00626/REP), DTI, October 2002.

[2] ICAO was formed in 1944, following the signing of the Chicago Convention, as a means to secure international co-operation and the highest possible degree of uniformity in regulations and standards, procedures and organisation regarding civil aviation matters. ICAO is a specialised agency of the United Nations.

A study undertaken in 2002, entitled, 'Wind Turbines and Aviation Interests – European Experience and practice' highlights the quite varying approaches and attitudes to wind power and how this has shaped policies, procedures and developments. The reasons include politics, geography, economics and history and have resulted in wind industries at varying stages of evolution. Broadly speaking, the conflict of interest between wind energy and aviation is less significant in some countries, albeit to varying degrees. For example, in Denmark the two seem to coexist most easily. In the Netherlands, also, aviation interests do not appear to impinge on wind energy developments. In Germany, frictions have appeared in the past between the two interests and may well increase in the future, but this has not prevented the rapid growth of wind development. In Sweden has there been a similar amount of interest in the issue as the UK, particularly with reference to the effects of turbines on technical systems. However, the tightest restrictions in Sweden come not from aviation specifically, but from other military activities unique to Sweden, such as radio links e.t.c.

2. BENEFITS OF IEA COOPERATION

It has become apparent that individual countries have rather different ways of approaching the issue of wind farms and their effects on aviation and radio transmission. Unsurprisingly, countries with large installed wind energy capacity, have well-developed and efficient systems for dealing with planning and approval issues. In contrast countries, where wind energy is still in its infancy, systems are still evolving. Some of the key differences, and similarities, include:

- The Planning, Assessment and Approval Process
- Aerodrome Safeguarding
- Technical Site Safeguarding – Civil Sites
- Technical Site Safeguarding – Military Sites
- Low Flying
- Marking and Illuminating
- Charting

Along with benefits, the growth of the wind energy sector has generated new issues. The member countries of IEA R&D Wind are always considering new opportunities for international collaboration to increase knowledge, understanding and to be proactive when dealing with new issues, before or as they arise. In view of the different approaches to the problems associated with wind farms and the aviation community it is important that the wind industry provide the opportunity for specialists from both the wind and aviation community to debate issues with the common objective to work as a partnership. One such opportunity is the Wind R&D Agreement and it is proposed that a Topical Expert Meeting, under Annex 11 of this agreement, be held to inform participants of the issues that exist, how these are being resolved and the latest developments on mitigating interference.

IEA Topical Expert Meeting No. 46

(17-18th March 2005)

Radar, Radio, Radio Links
and
Wind Turbines

Mark Dorrington
Future Energy Solutions

dti — Renewables Policy and Deployment Programme

Introductory note

- Wind power now an established source of electricity generation worldwide
- During 2003 the World's generating capacity grew by over 8.3GW, totalling 40GW
- 90% being installed in the countries that participate in the IEA R&D Wind agreement

dti Renewables Policy and Deployment Programme

IEA Annual Report 2003

Country	Total installed capacity MW	New installed capacity in 2003
Germany	14,609	2,608
United States	6,374	1,689
Spain	6,202	1,323
Denmark	3,114	225
Netherlands	905	227
Italy	904	116
United Kingdom	648 (900)	96
Sweden	404	59

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Different attitudes towards wind power

- Politics/history
- Economics
- Electricity demand
- Geography
- Technology
- Civil and military aviation interests

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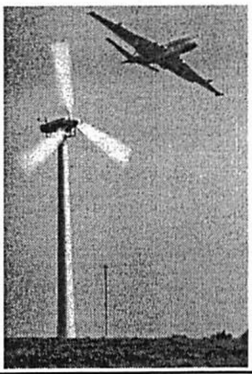
Renewables Policy and Deployment Programme

Wind Energy and Aviation Interests

Basically two ways in which a wind turbine or wind farm may impact upon aviation operations:

- Physical obstruction
- Effects of rotating blades on radar systems and navigational aids



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Renewables Policy and Deployment Programme

Wind Energy and Aviation Interests

Concerns over the potential for interference with radar systems and navigational systems

- Objections arise over potential effects on radar systems for both AD and ATC
- Conflicts between the aviation and wind community vary from country to country
- Must not forget issues surrounding planning and grid infrastructure
- Steps need to be taken to address potential conflicts

dti Renewables Policy and Deployment Programme

Wind Energy and Aviation Interests

Actions:

- Oversight and regulation by individual countries, harmonised by International co-operation - ICAO
- Technical studies (mitigation technologies, modelling etc.)
- Work in the UK - Programme led by the Department of Trade and Industry

dti Renewables Policy and Deployment Programme

Wind Energy, Defence and Civil Aviation Interests Working Group

Terms of Reference:

- To investigate issues of concern and improve understanding within both the aviation and wind energy industries
- To provide a clear strategic view on mitigation technologies
- Commission research and development studies

European perspective

(DTI report 2002 – "Wind Turbines and Aviation Interest – European Experience and Practice)

- Different approaches and attitudes to wind power and the aviation community
- In some countries aviation interest do not appear to impinge on wind developments
- Hence growth of wind farms varies between countries
- Lessons to be learnt?

dti Renewables Policy and Deployment Programme

Conclusion

- Growth of the wind energy sector has generated new issues
- Opportunities exist for member countries of the IEA R&D Wind to collaborate
- TEM 46 provides one such opportunity to debate issues and work as a partnership

12

IEA Topical Expert Meeting No. 46

(17-18th March 2005)

Radar, Radio, Radio Links
and
Wind Turbines

Mark Dorrington
Future Energy Solutions

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Renewables Policy and Deployment Programme

UK- energy from renewables

Energy White Paper goals:

- 10% of energy from renewables by 2010
- UK government has ambition to double renewable share of electricity to 20% by 2020
- Achieve 60% reduction in carbon dioxide by 2050

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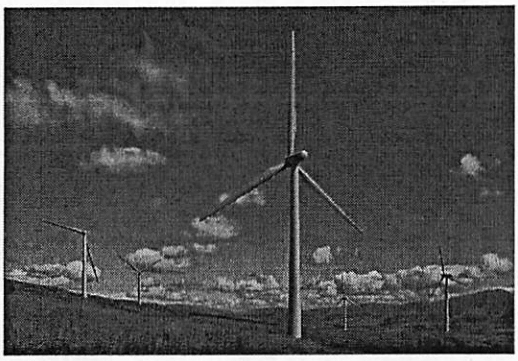
Renewables Policy and Deployment Programme

Role for wind energy

- Wind has become an important source of energy for the UK
- Total installed capacity ~1GW
- Potential for another 6GW before 2010



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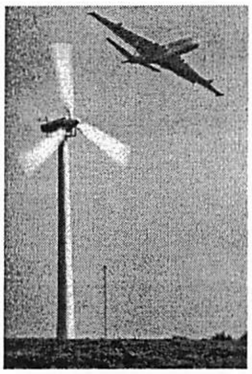
Renewables Policy and Deployment Programme

Wind Energy, Defence, and Civil Aviation Interests

- DTI committed funds to develop wind energy in the UK through its Technology Programme
- Recognise need to take full account of air safety and national defence
- Established Aviation Steering Group in 2001. Managed by Future Energy Solutions

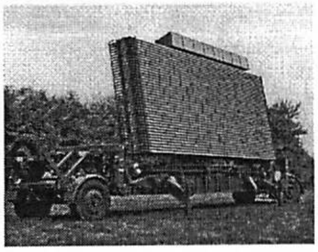


Aviation Steering Group (ASG)

Composition of ASG encompasses all major stakeholders:

- DTI; MoD; CAA; BWEA
- High level Ministerial Co-operation
- ASG meets every 3 months

Chaired by Kristian Armstrong - DTI



Wind Energy, Defence and Civil Aviation Interests

Aim of Aviation Steering Group:

To produce public domain guidance on the appropriate siting of both onshore and offshore wind turbines, with respect to their likely effects on defence and civil aviation interests

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Renewables Policy and Deployment Programme

Wind Energy, Defence and Civil Aviation Interests

Main objectives:

- To investigate issues of concern and improve understanding within both the aviation and wind energy industries in order to promote wind development
- To streamline and formalise the wind farm development application process
- To identify and evaluate issues as they arise and subsequently to generate research and development studies to address such issues

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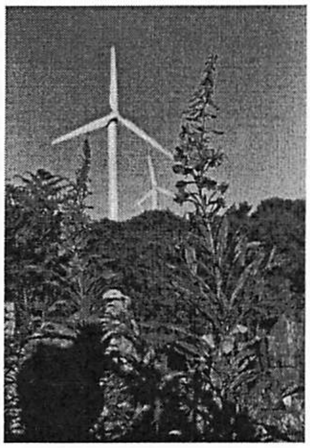
Renewables Policy and Deployment Programme

Wind Energy, Defence and Civil Aviation Interests

Objectives (continued):

- To generate guidance acceptable to all stakeholders
- Encourage the widespread adoption of the guidance
- To provide a clear strategic view on mitigation technologies, both present and in the future



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Renewables Policy and Deployment Programme

Wind Energy, Defence and Civil Aviation Interests

Other groups which form part of the overall programme:

Recently formed Aviation Strategic View Group:

- To provide a clear strategic view on mitigation technologies, both present and in the future

Number of sub-groups set up:

- Radar Sub-group
- Editorial Sub-group

Chaired by David Crookes - DTI

dti

Renewables Policy and Deployment Programme

Wind Energy, Defence and Civil Aviation Interests

Summary of Activities:

- Monitoring and Measurement (Consultation Information System, Assessment Methodology)
- Improved understanding of impacts on radar (MoD - air defence and air traffic control radars)
- Mitigating measures:
  - Advanced Digital Tracking
  - Additional radar
  - NATS/Raytheon study
  - Development of Stealth Blade technologies
  - Air Space rule changes/Mandatory Transponder Carriage

Wind Energy, Defence and Civil Aviation Interests

Summary of Activities (continued):

- Intention to produce revised Guidelines by October 2005
- To establish a clear strategic view for mitigation activities relating to wind farm development/radar interference

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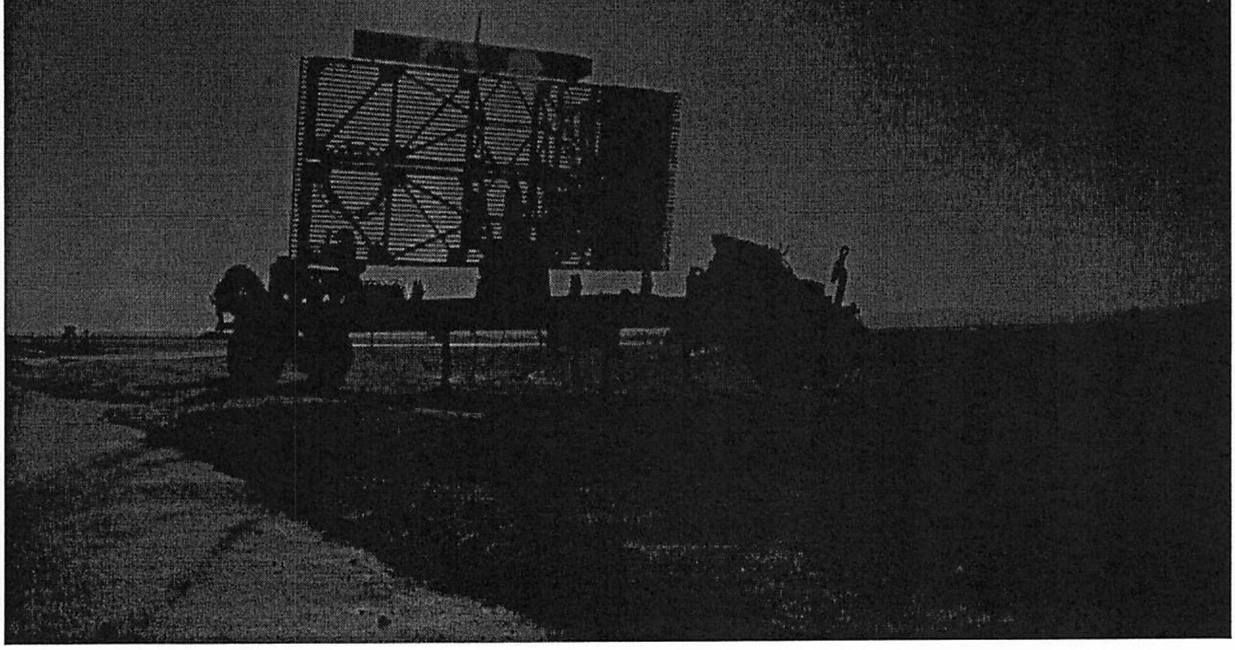
Renewables Policy and Deployment Programme

Wind Energy, Defence and Civil Aviation Interests

Conclusion

Develop International collaboration and partnerships to increase knowledge and understanding with common objective to resolve wind farm/aviation issues

Operational Impact of Wind Turbine Farms on Radar



Air Command & Control Operational Evaluation Unit, RAF Air Warfare Centre

Flight Lieutenant Ian 'Logic' Middleton

Sensors Team Leader

Scope

- Background
- Trial SWIFT CROFTER
  - 28/29 Jul 04 & 15/16 Sep 04
- Trial QUIXOTIC ZEPHYR
  - 23/24 Nov 04 & 13/14 Dec 04
- *Trial MISTRAL CROP*
  - *31 Mar - 05 Apr 05*
- Future Roadmap
- Questions?

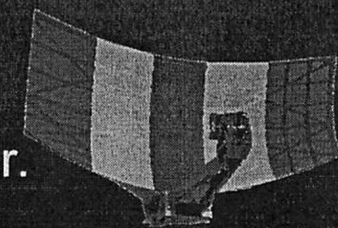
Dr Alistair Jolly
Radar Team Leader
Defence Science & Technology Laboratory

Background

- Air Traffic Control (ATC) observations
  - Mainly 'Clutter'
- Initial MOD study (1994)
  - RNAS Culdrose airfield radar - 'Watchman'
  - Short Range to Wind Turbines (~6km)
  - Observed Clutter and Obscuration
- **Concluded that Wind Turbines impact on operational use of Radar.**

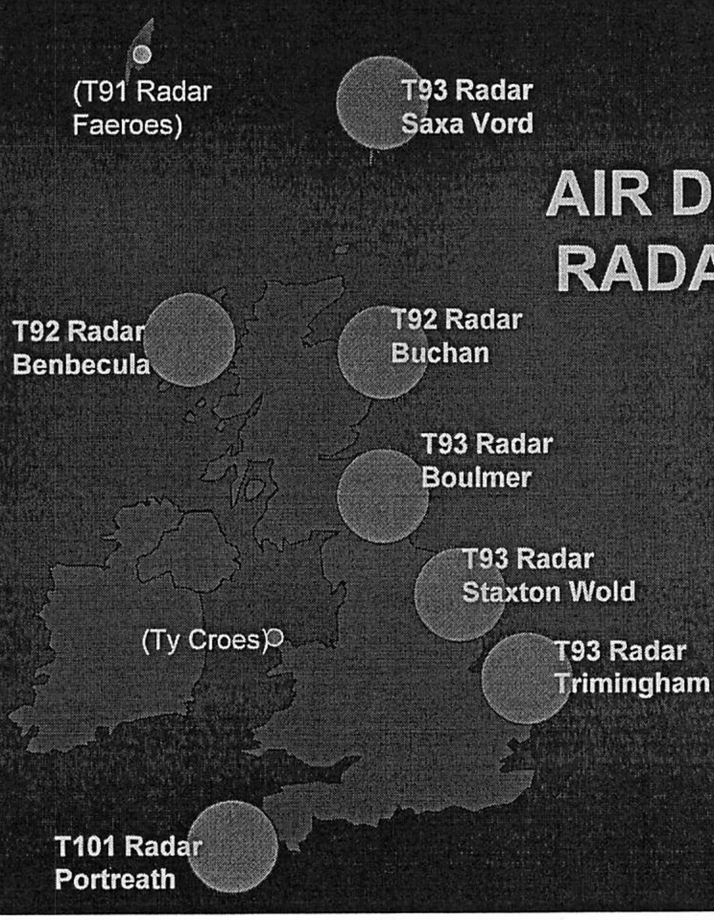
Original MOD Guidelines (Feb 95)

- Line of sight:
  - 60% of Instrumented Primary Radar Range
    - Interpreted as **74km**
    - Should be 250km+
  - 8km of Secondary Surveillance Radar (SSR)
- Based on Watchman trial
  - NOT an Air Defence (AD) Radar.



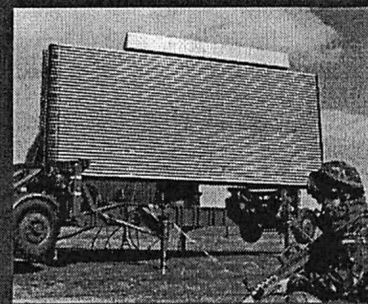
Air Command and Control Operational Evaluation Unit

AIR DEFENCE RADAR SITES



SWIFT CROFTER 1

- 28/29 Jul 04



- MOD aim:
  - Determine effects of wind turbine farms on AD radars
- Scoping Trial
  - Initial investigation
  - Inform Phase 2 design
- Type 101 Radar
  - S Band Passive Phased Array
- Ovenden Moor Wind Farm
  - 23 Turbines
- Chinook and Tucano.

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SWIFT CROFTER 2

- 15/16 Sep 04

- Wind Turbine Farm
  - Llandinam ('P&L')
  - 103 Mitsubishi turbines.

Air Command and Control Operational Evaluation Unit

SWIFT CROFTER 2

- 15/16 Sep 04

- Type 101 Radar (Primary and Secondary)
  - Location: 'Clee Hill'
  - Range to Turbines: ~57km
- Aircraft
  - Hawk (upper beam effects)
  - Dominie (GPS recording)
  - King Air (full Differential GPS recording)
  - Tucano
  - *Chinook (cx due to ac serviceability).*

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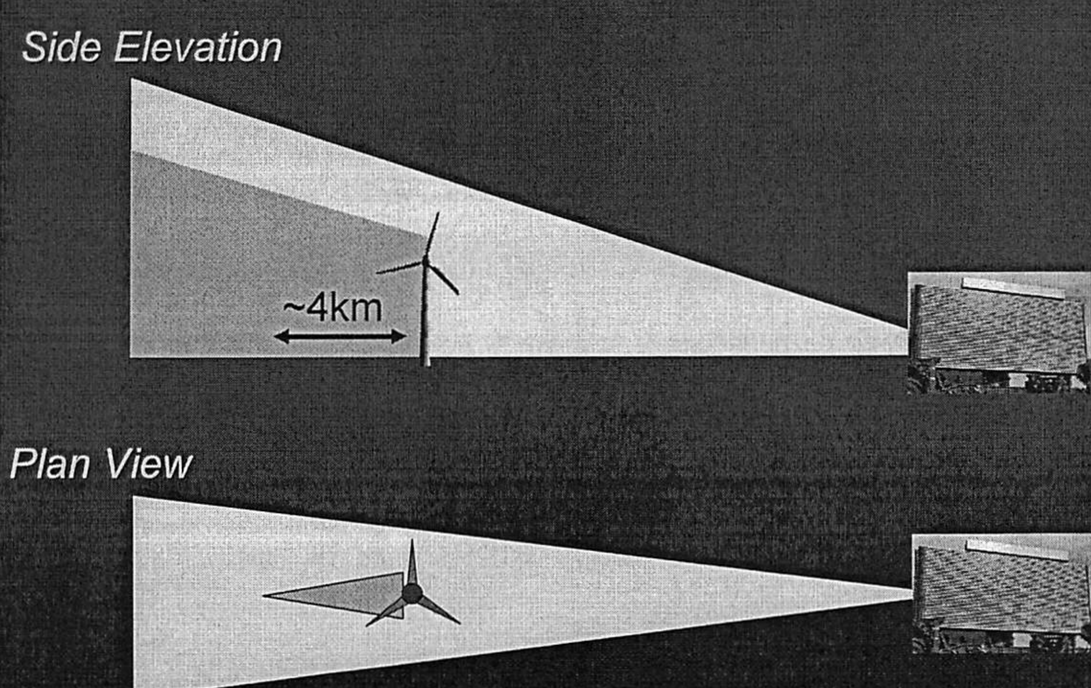
Shadow Effect



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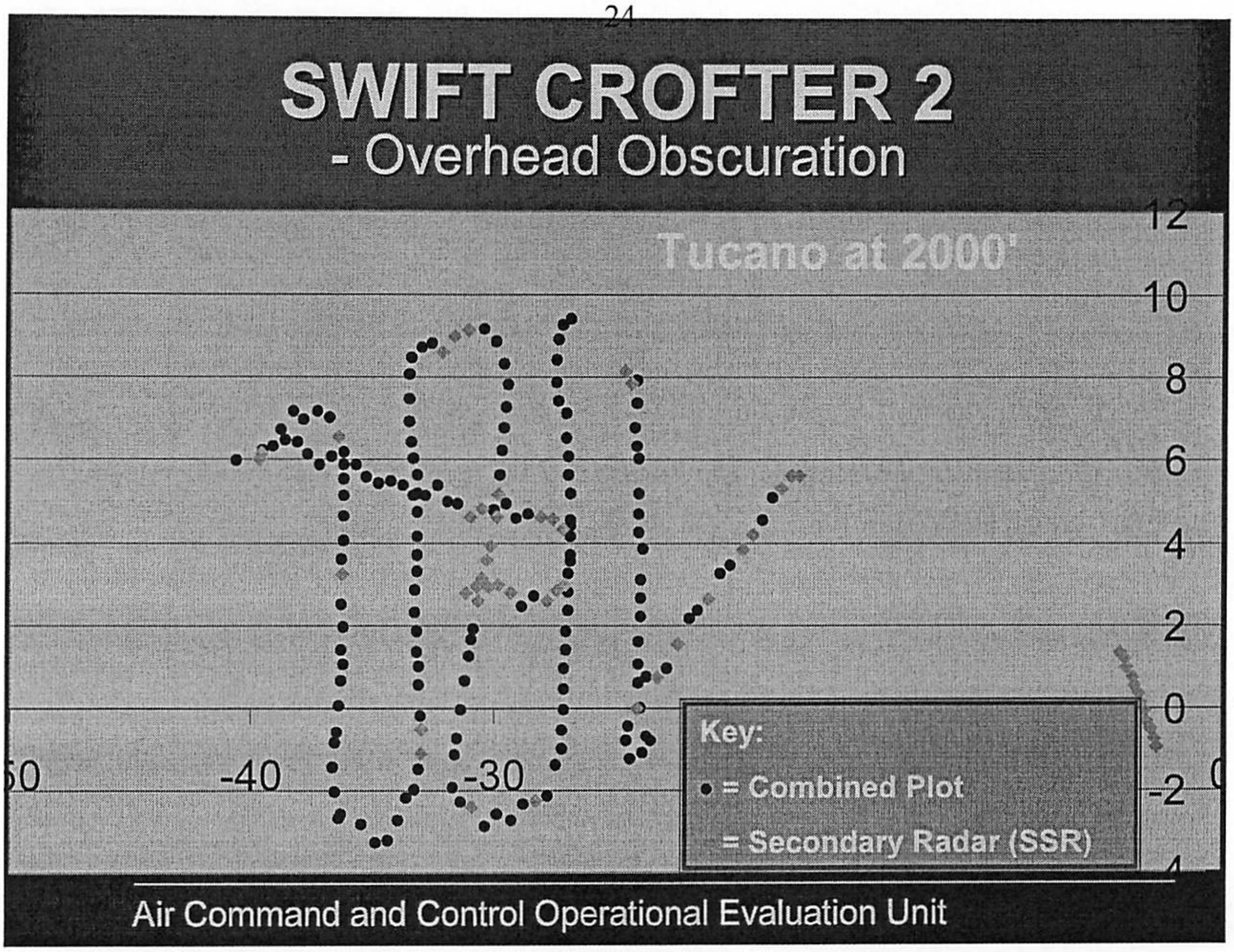
SWIFT CROFTER 2
- Overhead Obscuration
Tucano at 2000'
12
10
8
6
4
2
0
-2
-40
-30
Key:
= Combined Plot
= Secondary Radar (SSR)
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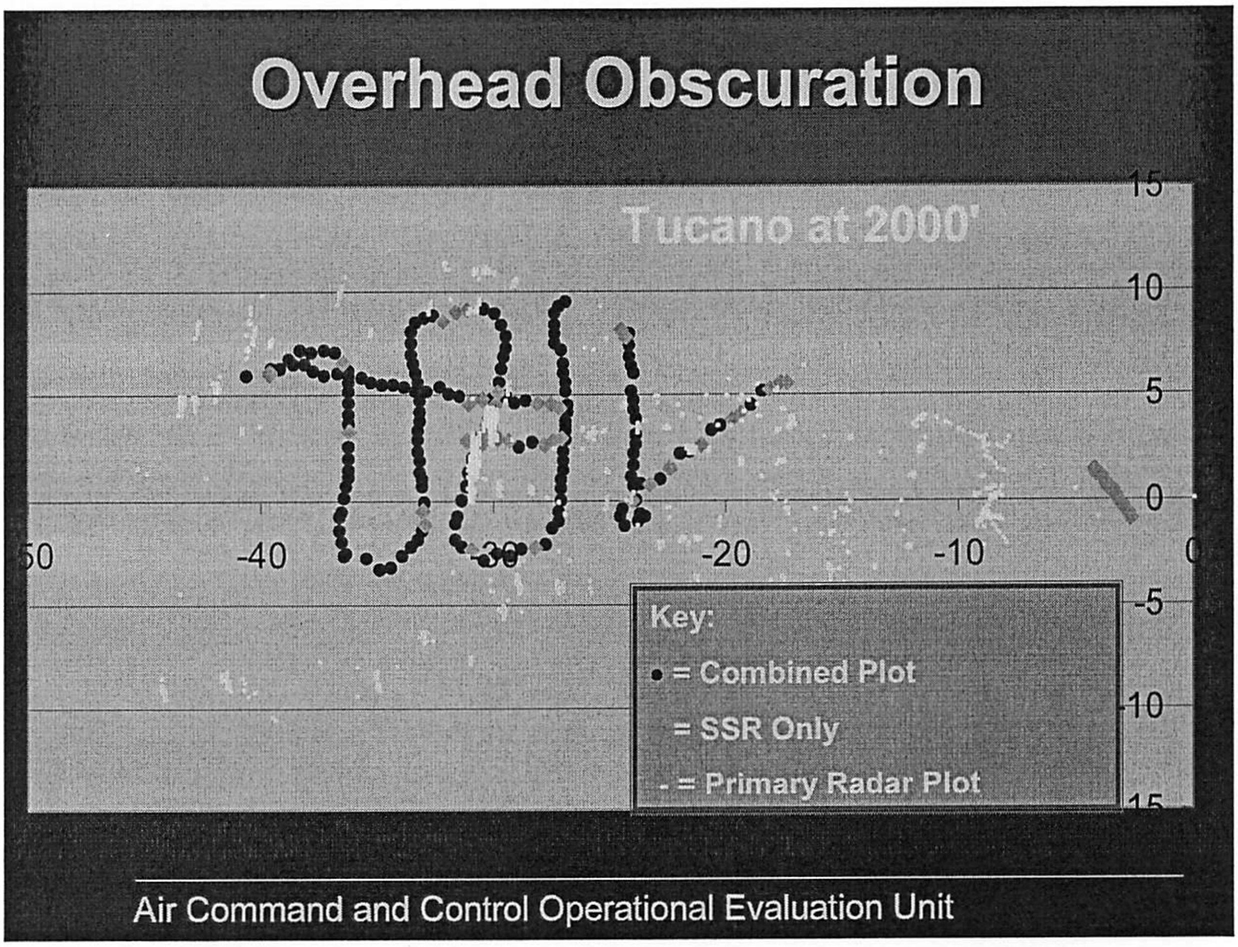
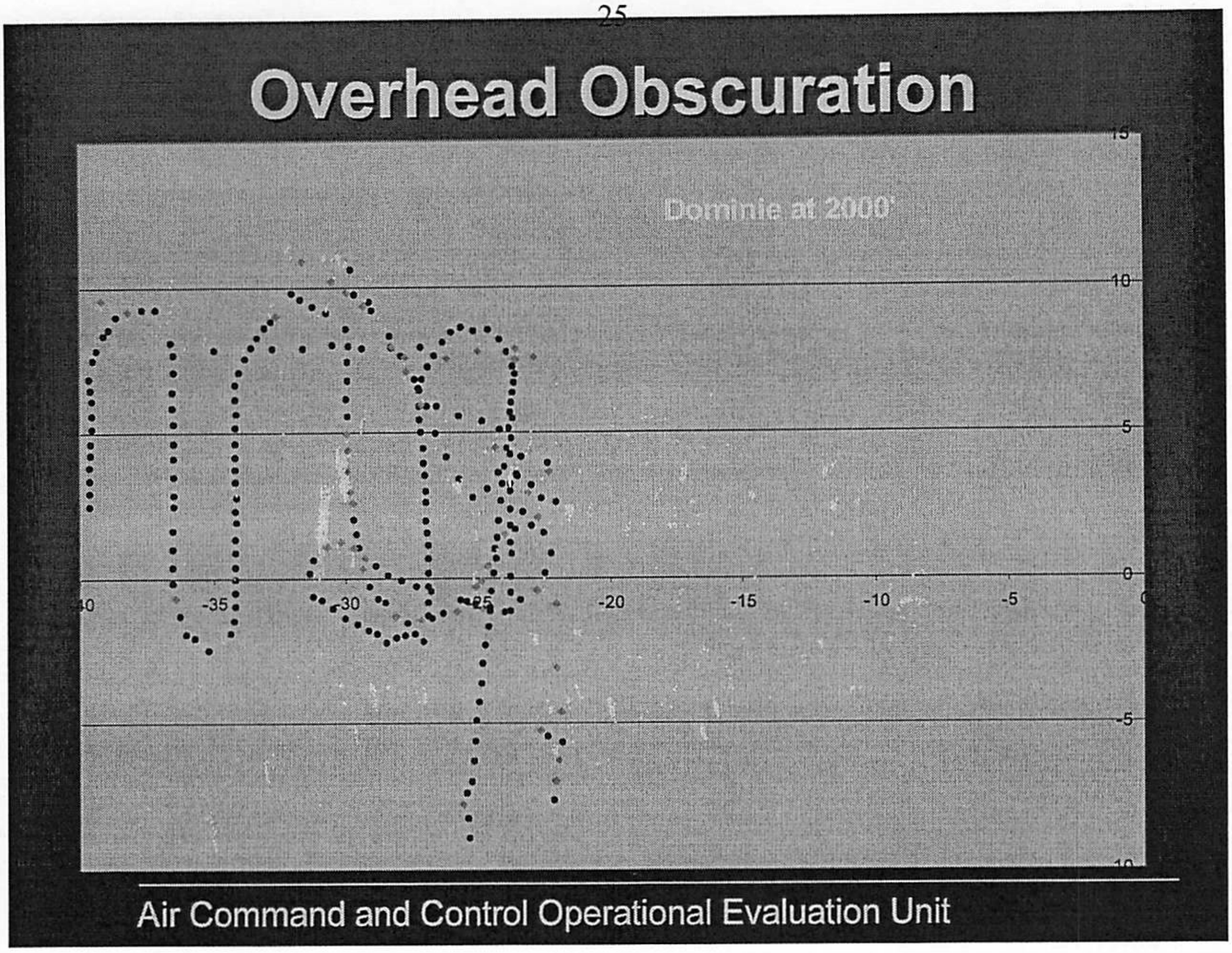
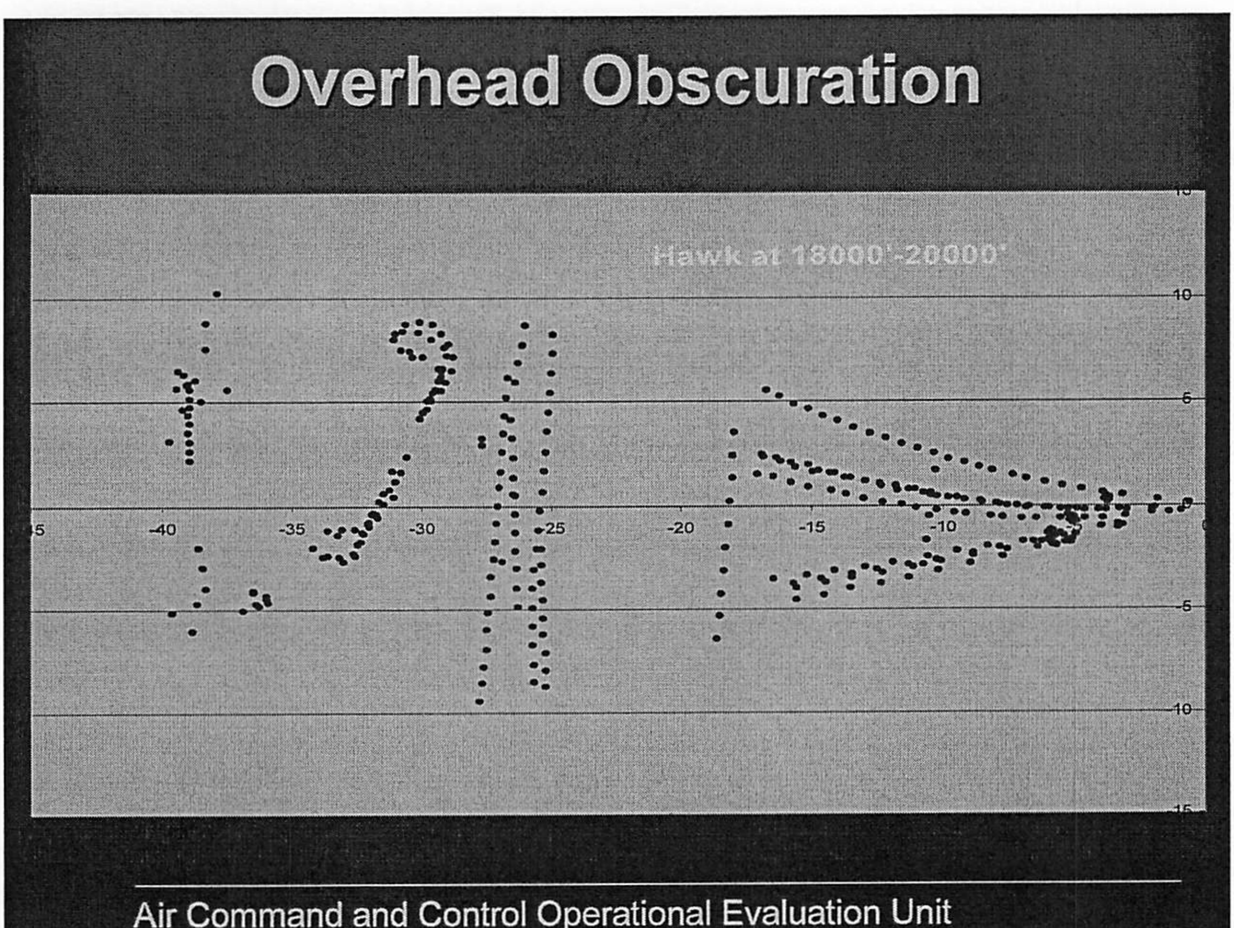
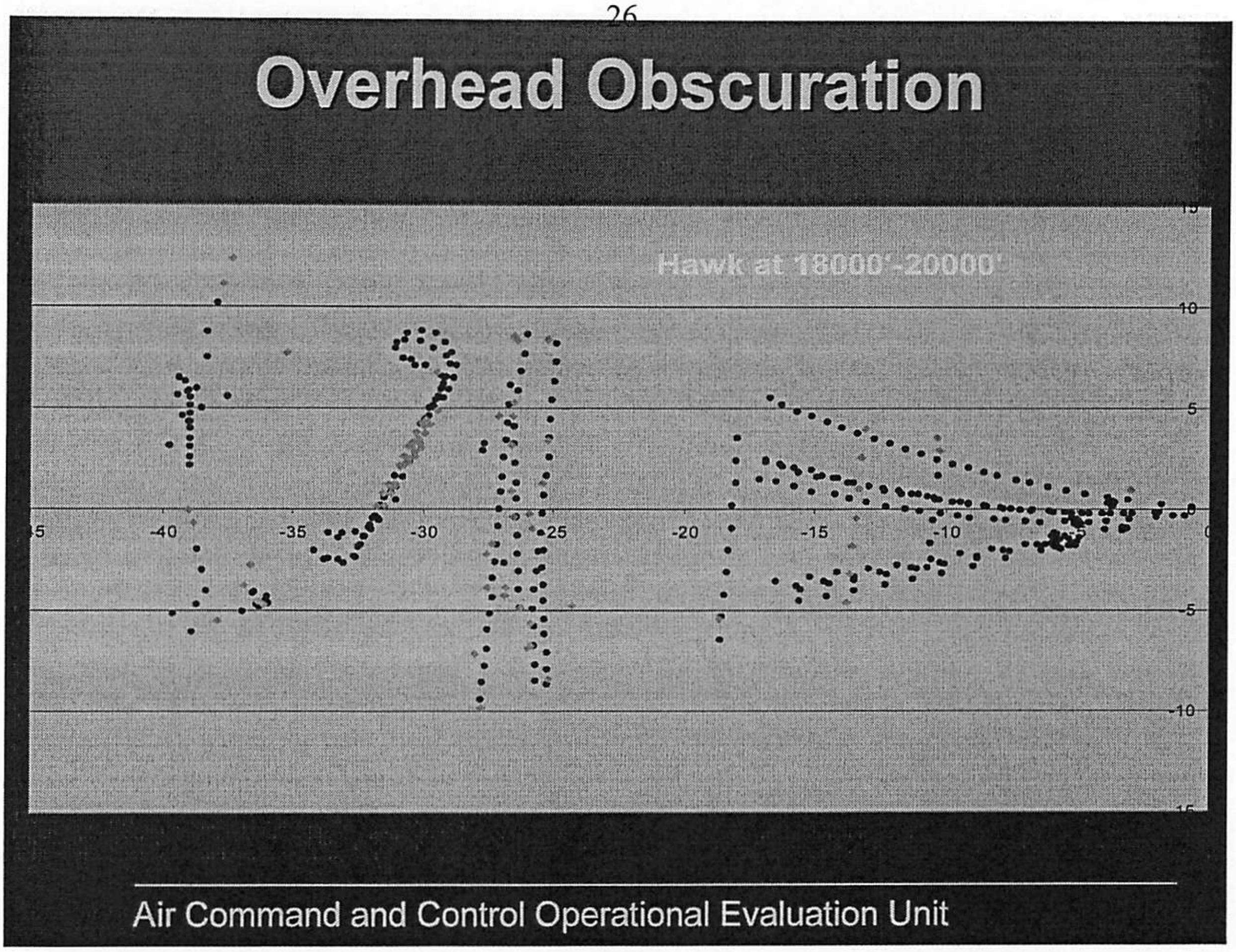
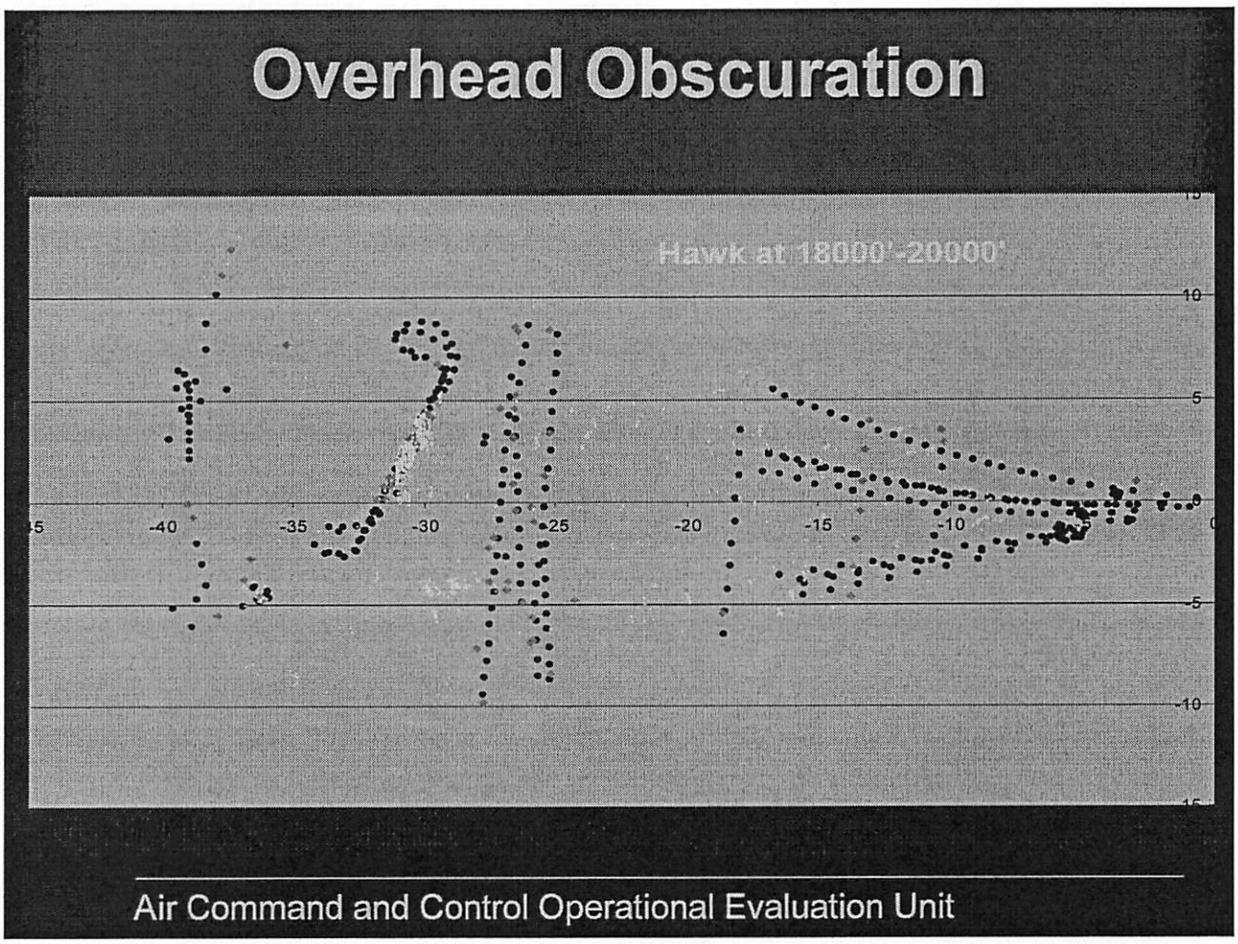
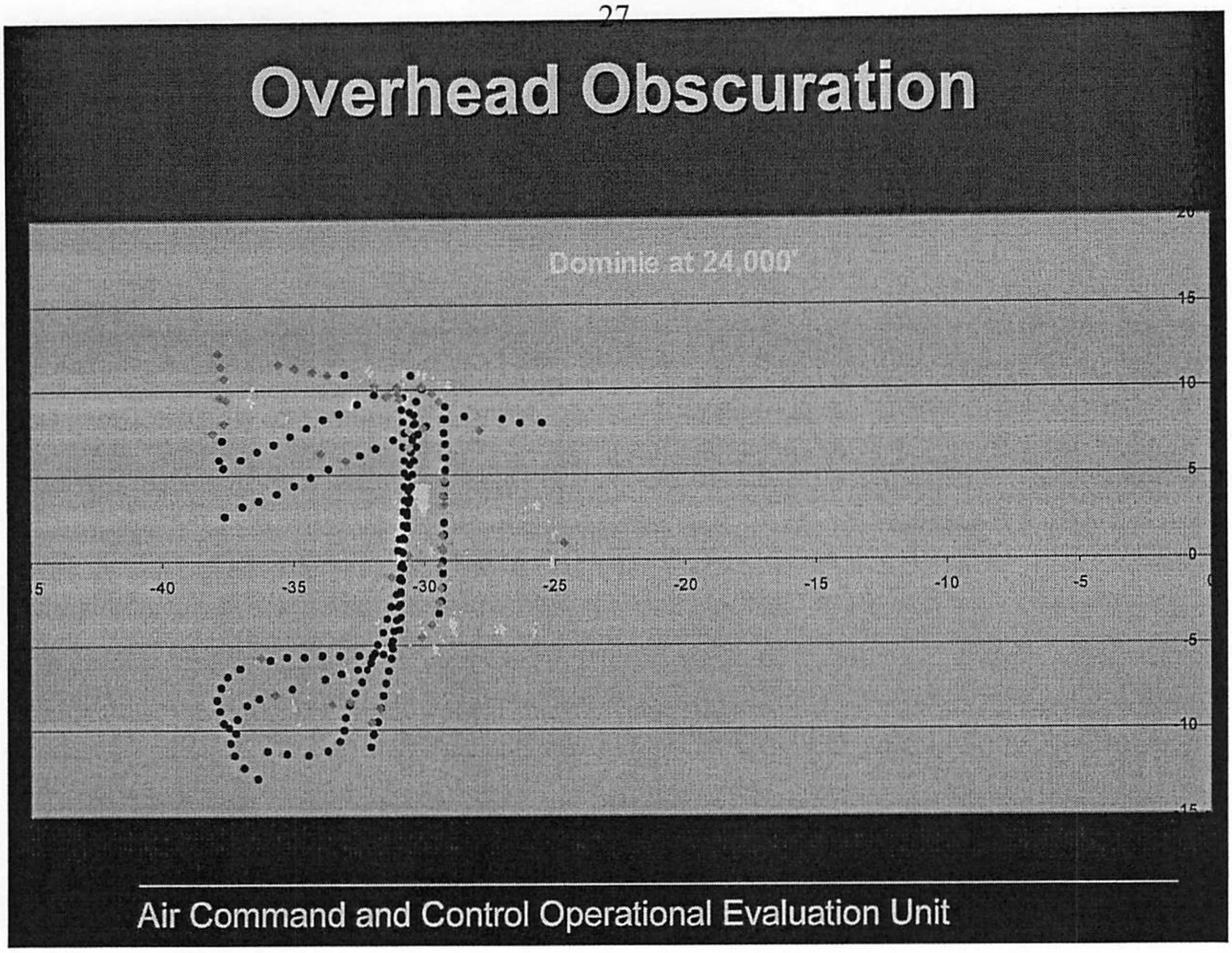

Overhead Obscuration
Tucano at 2000'
15
10
5
0
-5
-10
-40
-30
-20
-10
Key:
= Combined Plot
= SSR Only
= Primary Radar Plot
Air Command and Control Operational Evaluation Unit

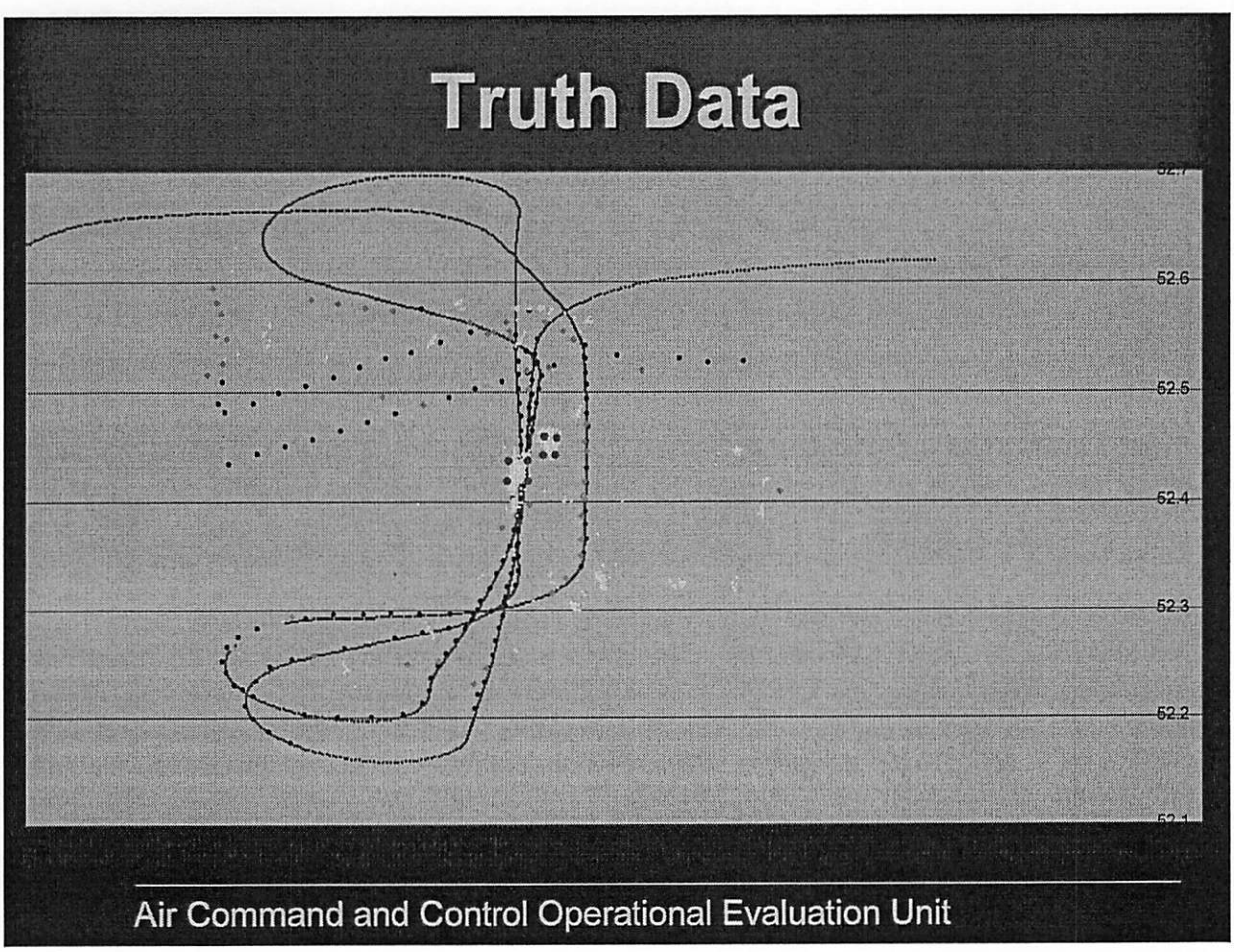

Overhead Obscuration
Dominie at 2000'
10
5
0
-5
-35
-30
-20
-15
-10
-5
Air Command and Control Operational Evaluation Unit

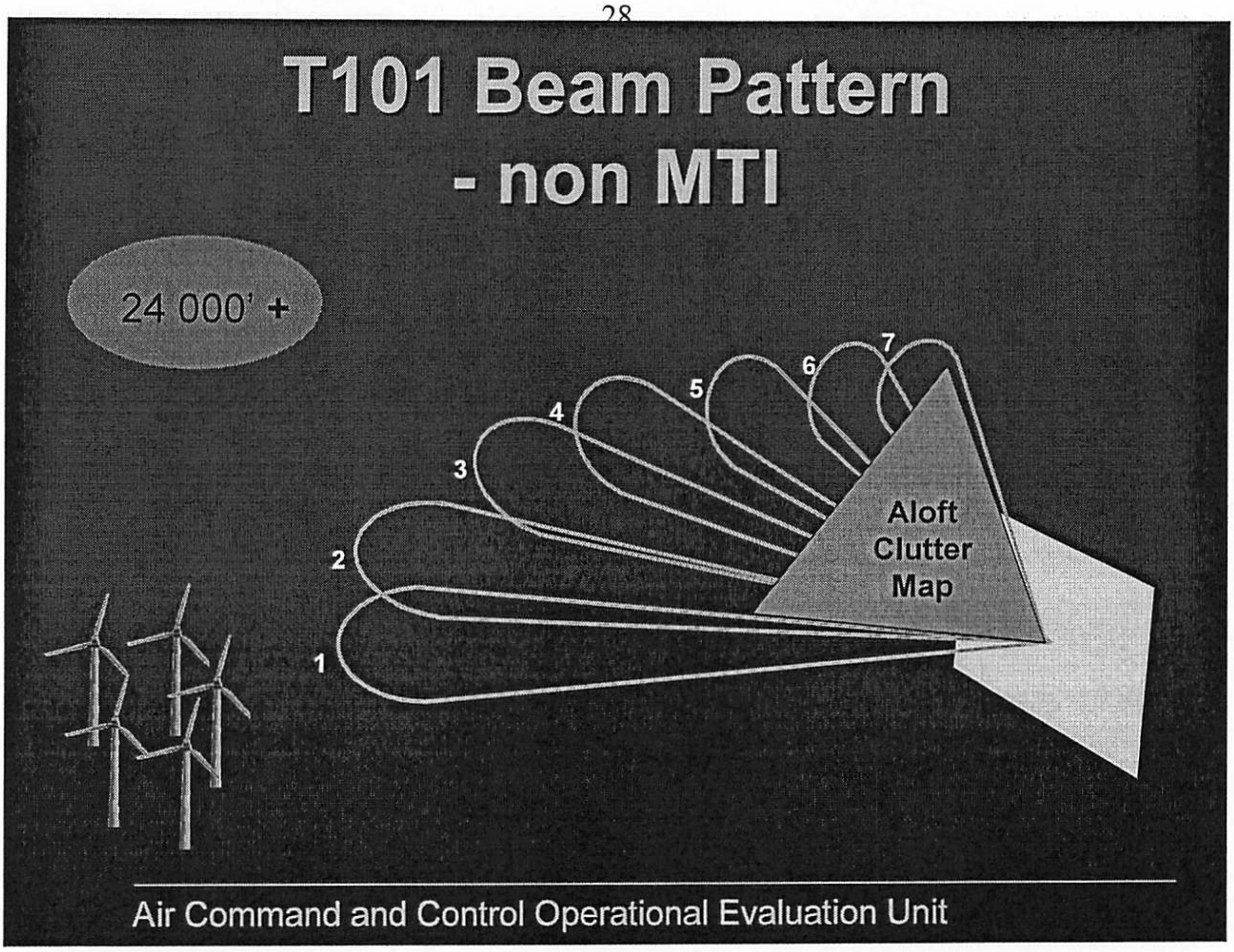

Overhead Obscuration
Hawk at 18000'-20000'
10
5
0
-5
-10
-40
-35
-30
-25
-20
-15
-10
Air Command and Control Operational Evaluation Unit

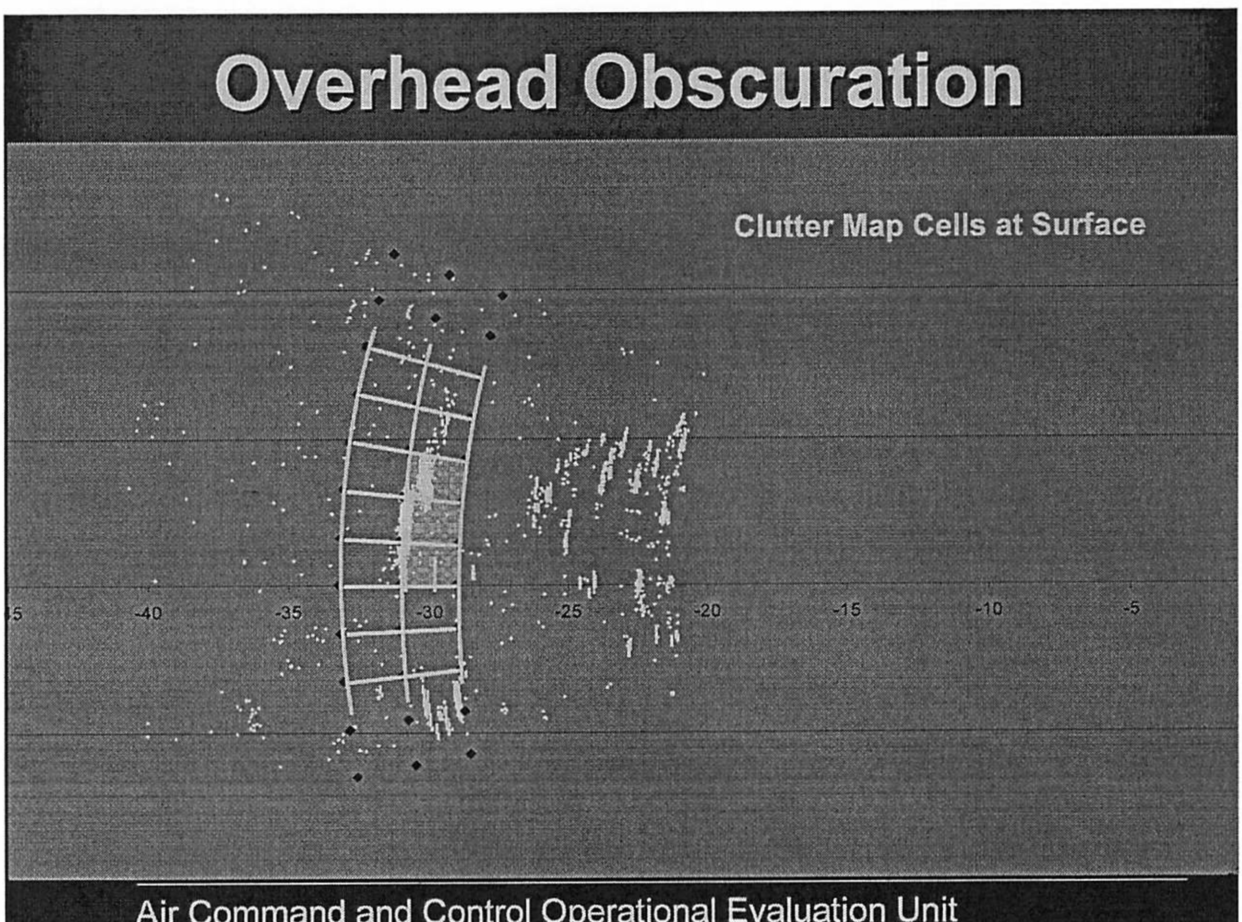

Overhead Obscuration
Hawk at 18000'-20000'
-40
-35
-30
-25
-20
-15
-10
10
5
0
-5
-10
Air Command and Control Operational Evaluation Unit

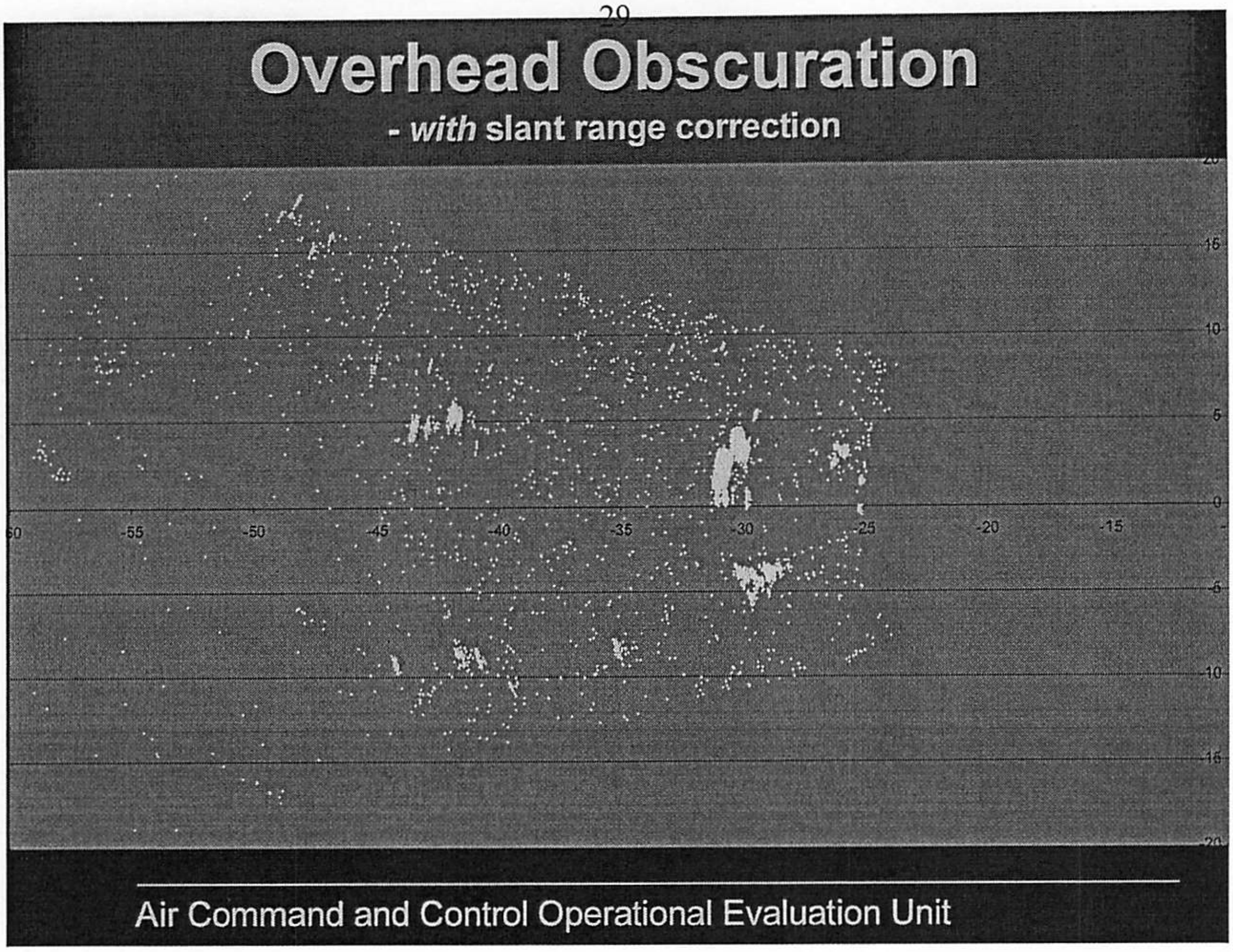

Overhead Obscuration
Hawk at 18000'-20000'
-40
-35
-30
-25
-20
-15
-10
10
5
0
-5
-10
Air Command and Control Operational Evaluation Unit

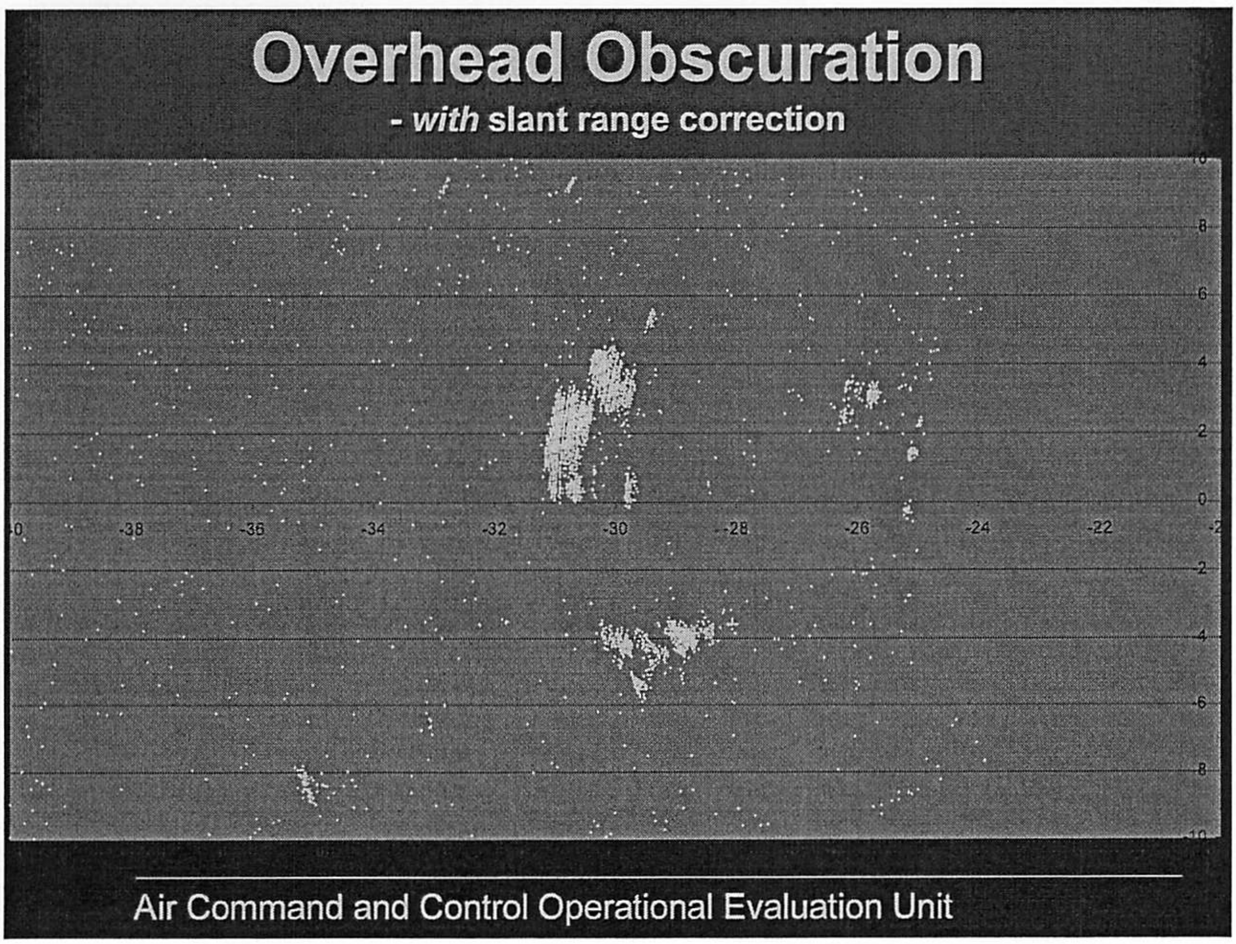

Overhead Obscuration
Dominie at 24,000'
15
10
5
0
-5
-10
-40
-35
-30
-25
-20
-15
-10
-5
Air Command and Control Operational Evaluation Unit

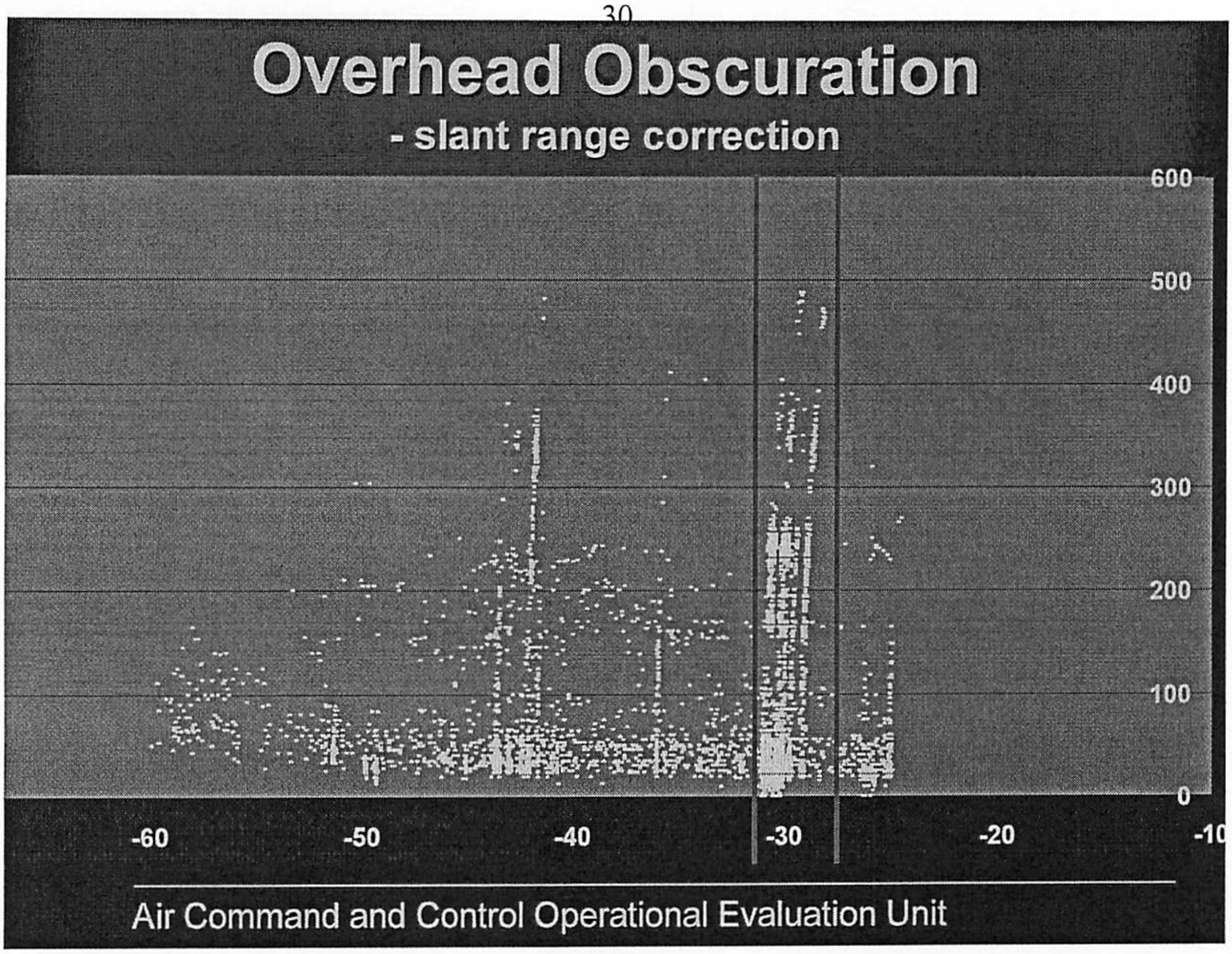

Truth Data
52.6
52.5
52.4
52.3
52.2
Air Command and Control Operational Evaluation Unit

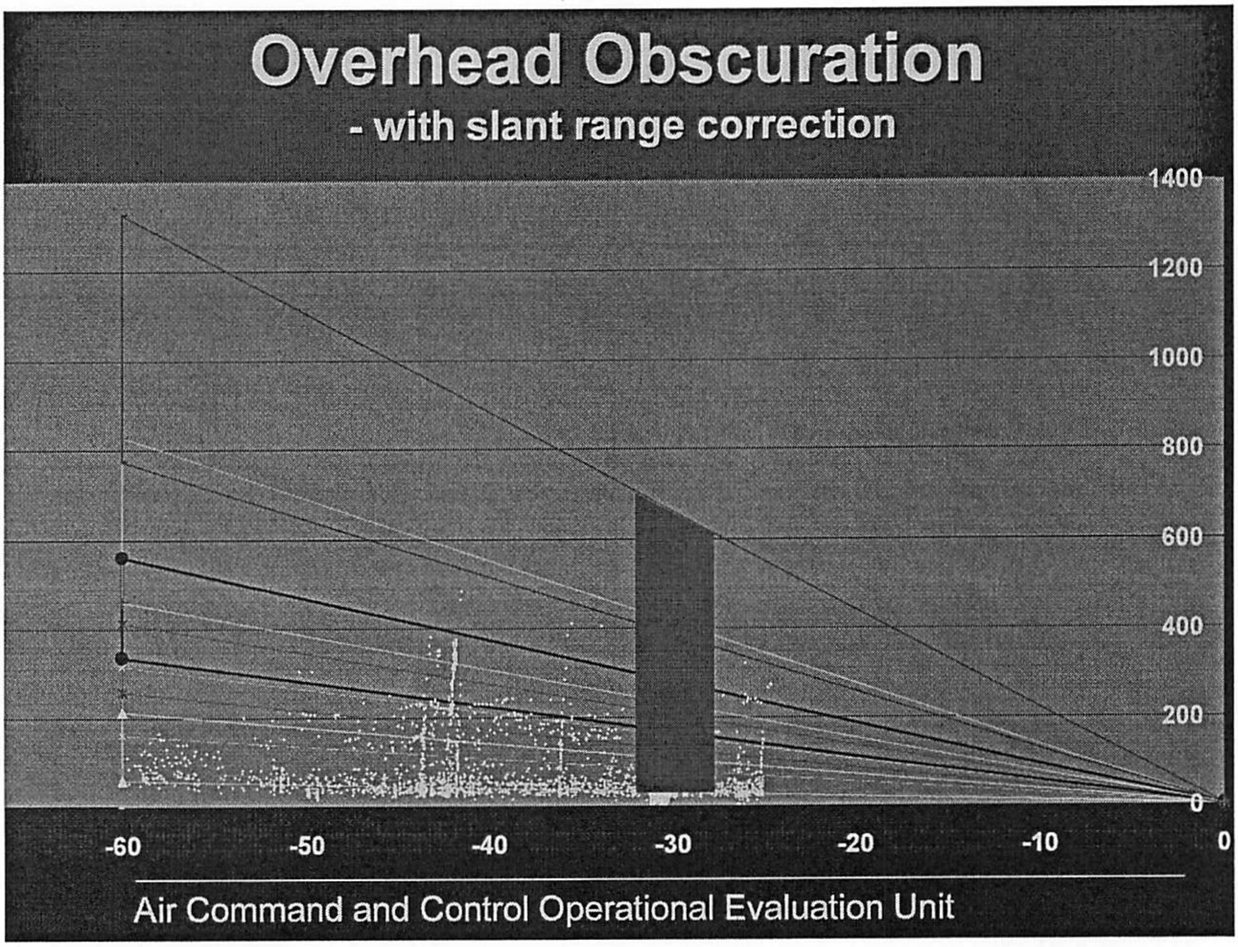

T101 Beam Pattern
- non MTI
24 000' +
1
2
3
4
5
6
7
Aloft Clutter Map
Air Command and Control Operational Evaluation Unit


Overhead Obscuration
Clutter Map Cells at Surface
-40
-35
-30
-25
-20
-15
-10
-5
Air Command and Control Operational Evaluation Unit


Overhead Obscuration
- *with* slant range correction
-55
-50
-45
-40
-35
-30
-25
-20
-15
Air Command and Control Operational Evaluation Unit

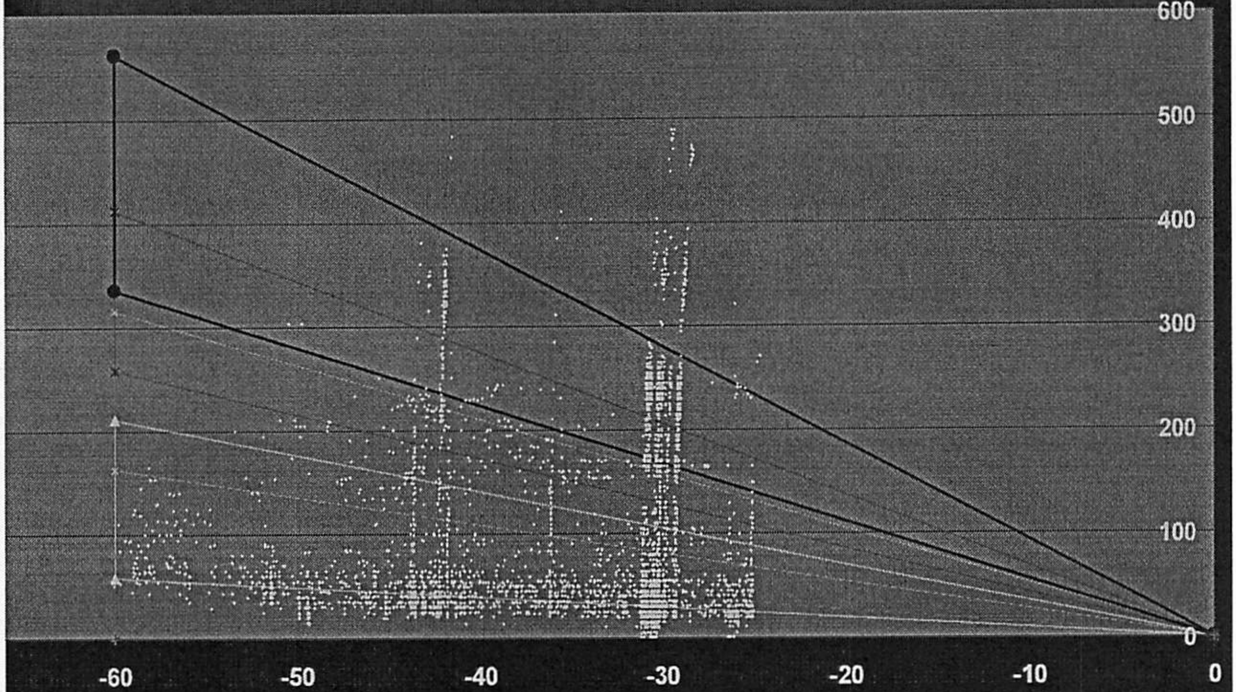

Overhead Obscuration
- *with* slant range correction
-38
-36
-34
-32
-30
-28
-26
-24
-22
Air Command and Control Operational Evaluation Unit


Overhead Obscuration
- slant range correction
600
500
400
300
200
100
0
-60
-50
-40
-30
-20
-10
Air Command and Control Operational Evaluation Unit


Overhead Obscuration
- with slant range correction
1400
1200
1000
800
600
400
200
0
-60
-50
-40
-30
-20
-10
0
Air Command and Control Operational Evaluation Unit

Overhead Obscuration

- with slant range correction



SWIFT CROFTER

- Conclusions

- 74km range is irrelevant
  - Should be 'Radar Line of Sight'
- 'Overhead Obscuration'
  - Height: All beams
  - Likely clutter map effect (only on Normal Radar Beam)
  - Possibly due to Elevation Sidelobes
- 'Shadow' Effect behind Turbines
  - Approx 4km on this occasion
  - Height unknown
  - Possible Background Averager problem (1km only?)
  - Possible Beam 1 Clutter Map
  - Not due to pre-compression limiting (effect too small)

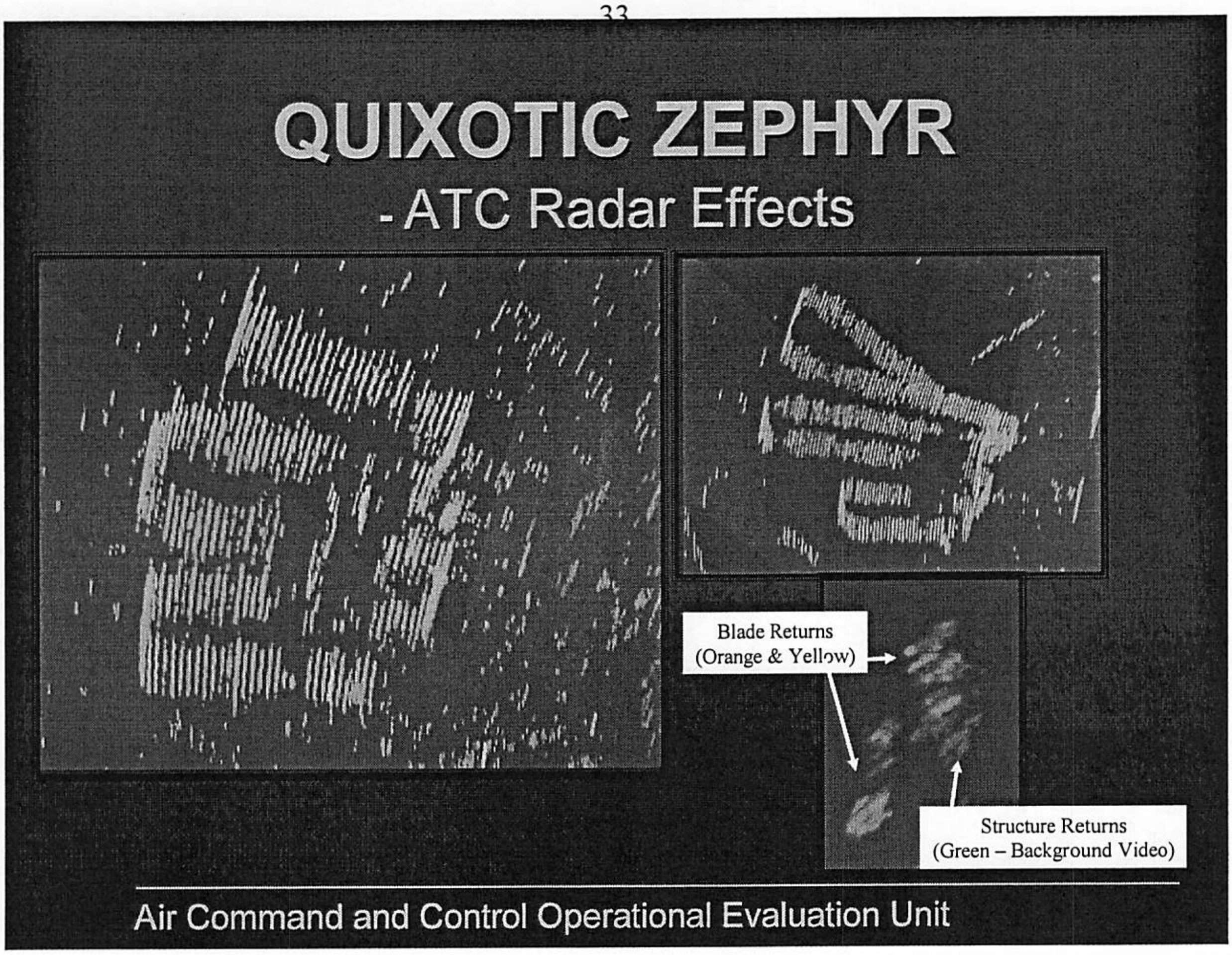
SWIFT CROFTER
- Conclusions

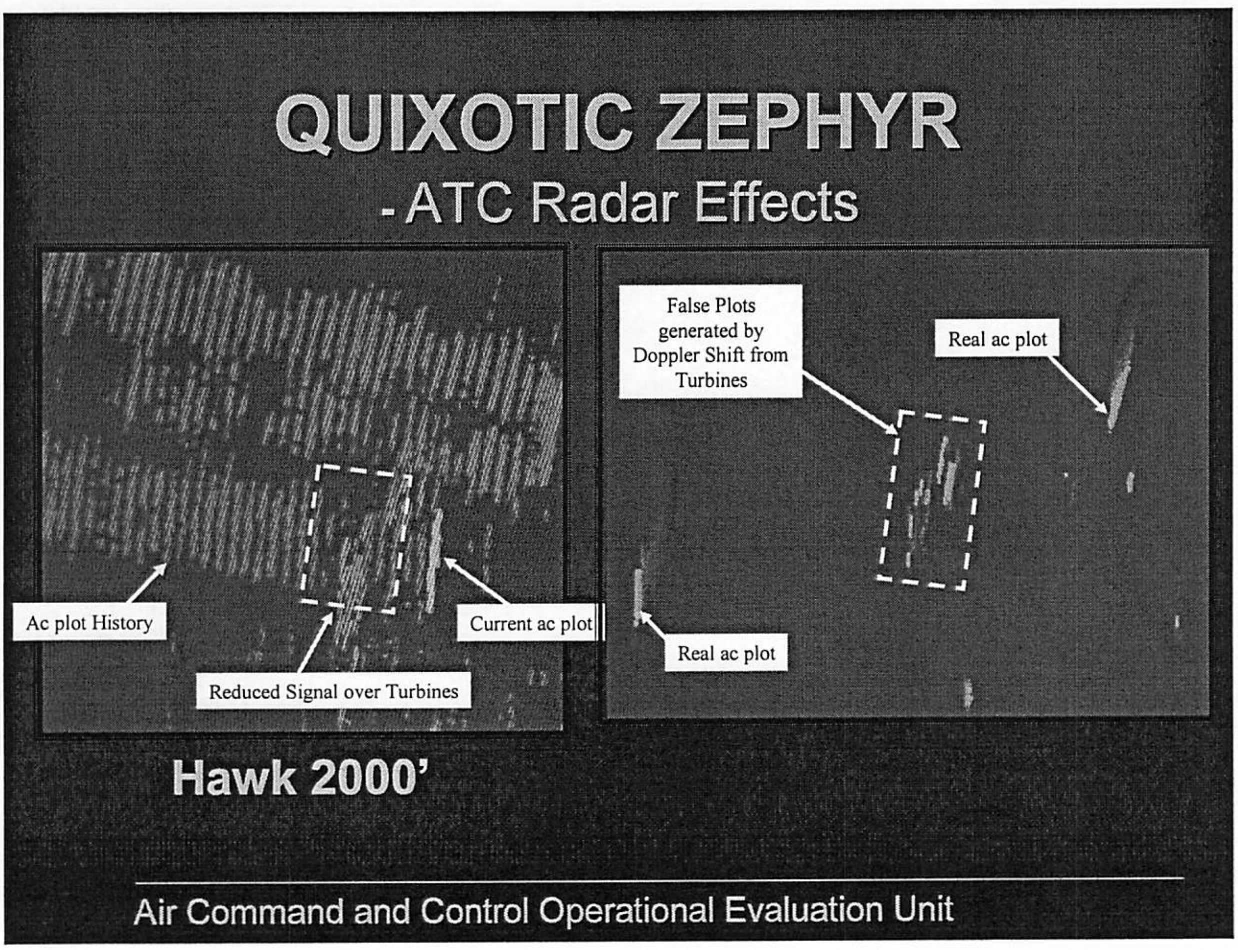
- Displayed Clutter
  - Minor clutter returns – post processed
  - No operational impact with Operator Intervention
- **No** other effect on low-level coverage.

QUIXOTIC ZEPHYR
- ATC Radar Effects

- Separate study
  - ATC Watchman Radar **not** AD Radar
- Overhead obscuration
  - Reduced Probability of Detection over Turbines
  - Displayed clutter
- Shadow/Obscuration region
  - Behind AND in front

Air Command and Control Operational Evaluation Unit


QUIXOTIC ZEPHYR
- ATC Radar Effects
Blade Returns
(Orange & Yellow)
Structure Returns
(Green – Background Video)
Air Command and Control Operational Evaluation Unit


QUIXOTIC ZEPHYR
- ATC Radar Effects
Ac plot History
Reduced Signal over Turbines
Current ac plot
False Plots
generated by
Doppler Shift from
Turbines
Real ac plot
Real ac plot
Hawk 2000'
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Roadmap

- Output of QUIXOTIC ZEPHYR
  - Formal Report Late Mar 05
- Trial MISTRAL CROP
  - Mar/Apr 05
  - DSTL scientific study
    - Pulse-to-Pulse analysis for T101
  - OEU Trial
    - Digitised Raw Video (beam by beam)
  - Inform technical solutions for MOD
- Other UK Radars
  - T92 (FPS-117) & T93 (AR-320)
  - Also suffer interference – extent unknown.

Questions?

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Air Command and Control Operational Evaluation Unit

Possibilities and problems

Radar and windturbines

TNO Fysisch en Elektronisch Laboratorium

L.J. van Ewijk, Senior research scientist

Contents

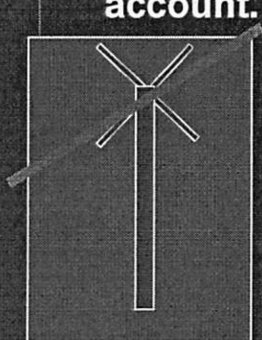
- Research overview at TNO / Background
- Basic assumptions for analysis
- Theoretical background
  - Software development
  - Validation
- Objects suitable for analysis
- Example results
  - Shadowing
  - Monopulse analysis

Research overview at TNO/background

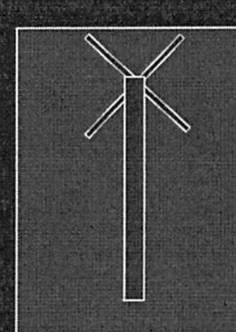
- **Background:**
  - Royal Netherlands Air Force initiated research in 1996, because a large amount of windmills were planned in a northern Netherlands province.
- **Research**
  - Basic research to effect of shadowing by windturbines, including algorithm development and laboratory testing (RNLAF).
  - Evaluation of wind turbine effect by field measurement and comparison to developed algorithm (RNLAF).
  - Various investigations involving air control radar and wind turbines.
  - Various investigations involving surface traffic control and wind turbines, both inshore and offshore.
  - Research for public services and private companies, mostly undisclosed.
  - Ongoing analysis of new plans (RNLAF).

Basic assumptions for analysis

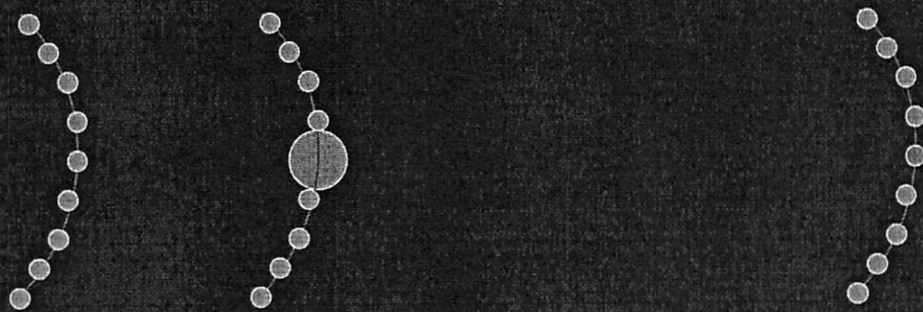
- **Shadowing is the important part of influence on radar by wind turbine.**
- **The appearance of ghost targets is investigated as well.**
- **At later stages monopulse direction finding also became an issue.**
- **Modulation effects by rotating blades are not taken into account.**



- **Actually, reflection by turbine blades is not taken into account.**

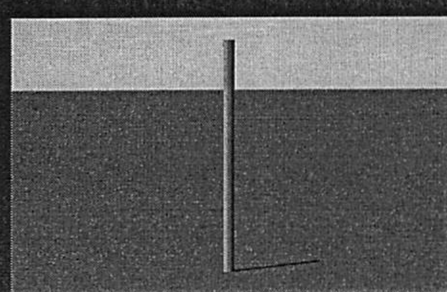


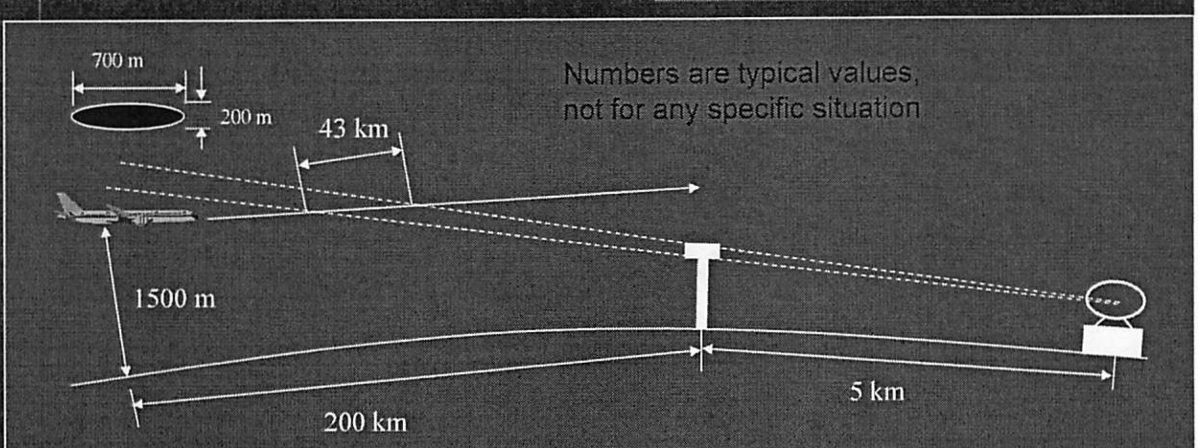
Theoretical background



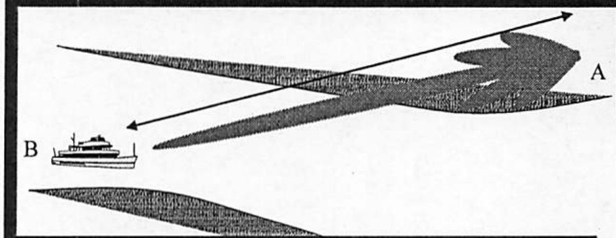
- A plane wave with Huygens sources travels undisturbed
- When an obstacle is in the path, some sources are not propagated
- This is the same as adding a negated extra source due to the obstacle

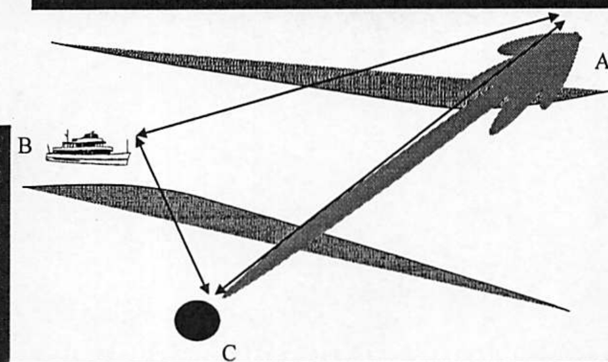
Theoretical background shadow

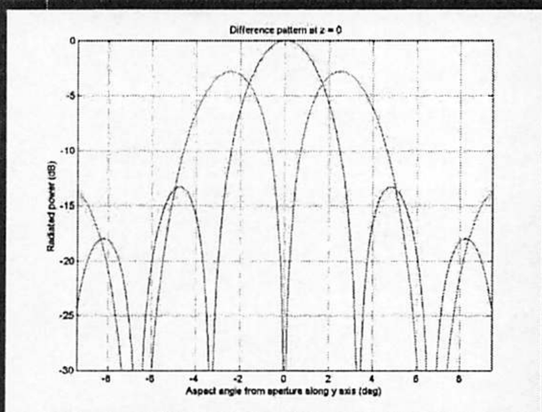




Theoretical background (2)





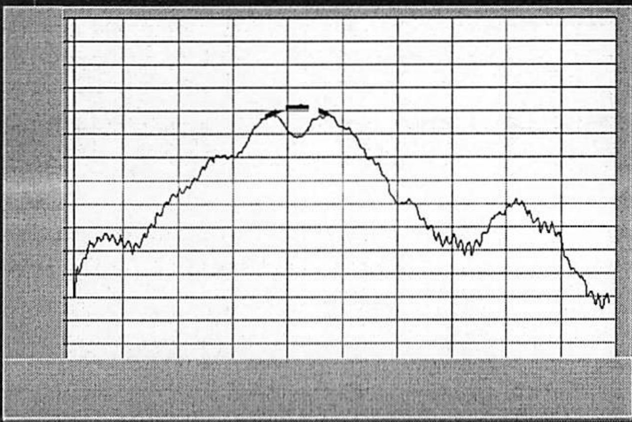


- Ghost targets appear for air surveillance radars as well, dependent on side lobe suppression.

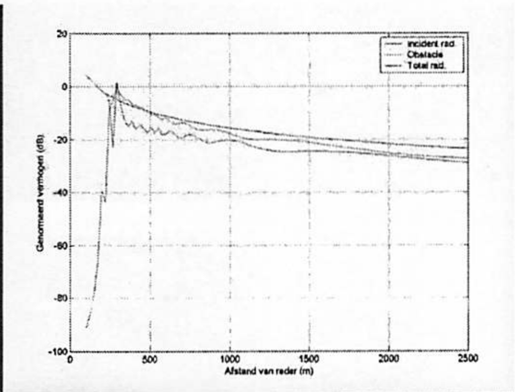
Objects suitable for analysis

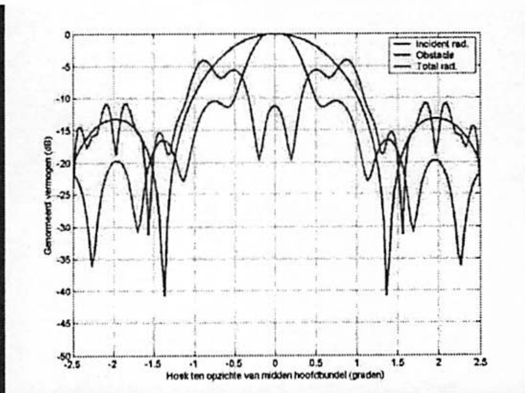
- The objects can obstruct only small part of the radar beam.
- Large buildings, blocking a major part of the beam are not analysed.
- Obstructions are assumed to be completely blocking, no transmission is incorporated.

Example results

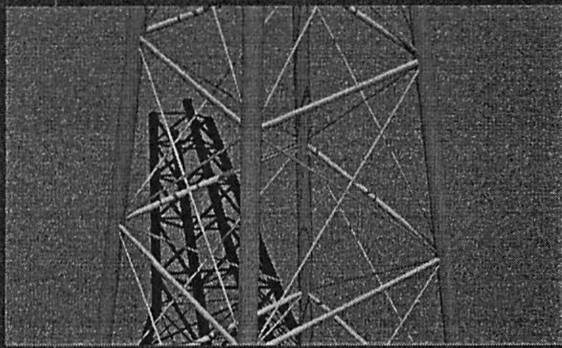


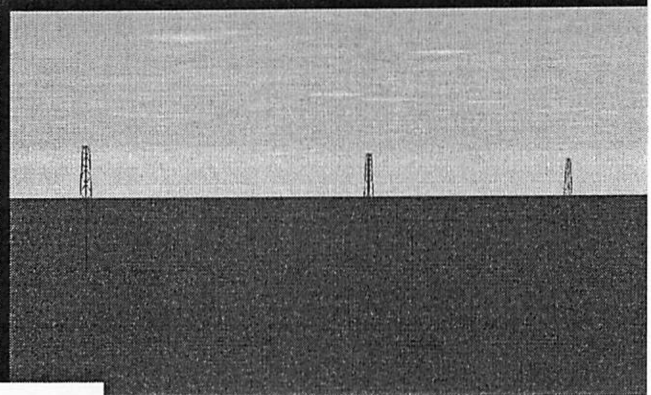
- Measured result in a helicopter, 50 km from radar.
- Wind turbine close to radar.
- Compared to simulated data, reasonable agreement.
- Laboratory validation has also been done on scaled cylinder.

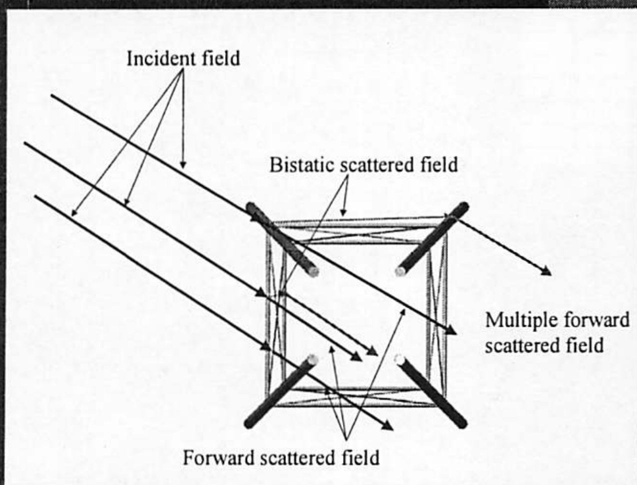




Decrease power (dB)	Decrease detection range (%)	Decrease power (dB)	Decrease detection range (%)
0.25	2.8	2.75	27.1
0.5	5.6	3.0	29.2
0.75	8.3	3.25	31.2
1.0	10.9	3.5	33.2
1.25	13.4	3.75	35.1
1.5	15.9	4.0	36.9
1.75	18.2	4.25	38.7
2.0	20.6	4.5	40.4
2.25	22.8	4.75	42.1
2.5	25.0	5.0	43.8

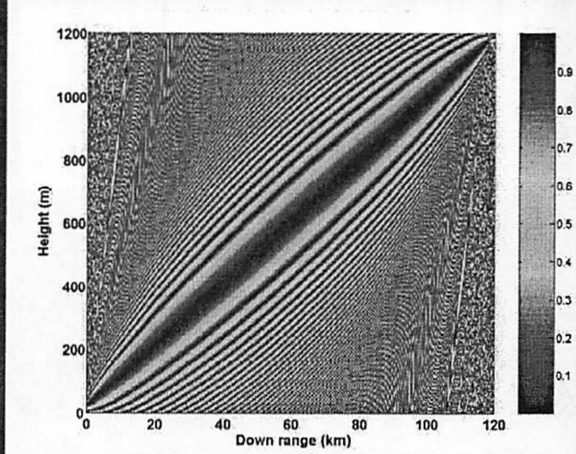


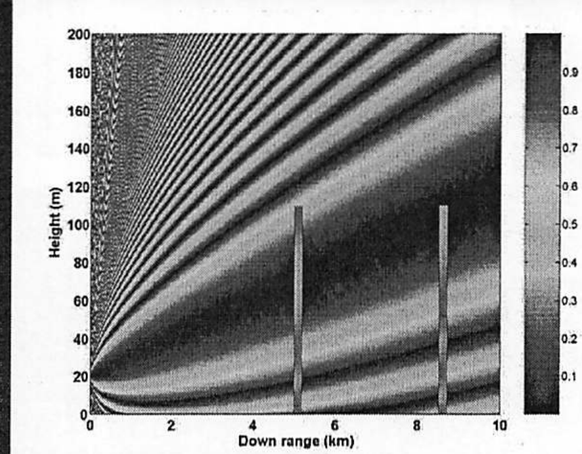




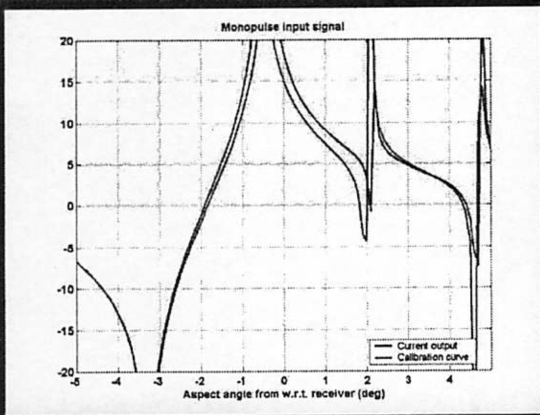
- **Framework masts analysed recently.**
- **It appeared that the amount of metal was vital, not the shape.**

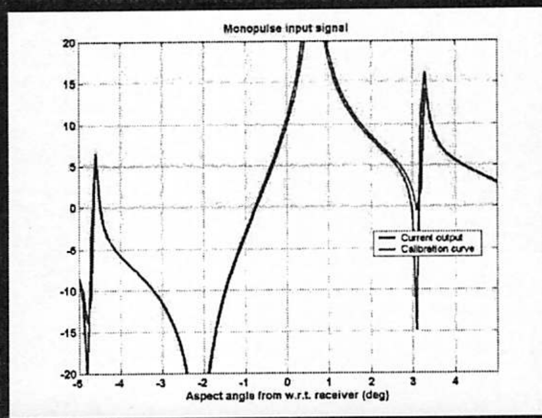
Contributing part of mast

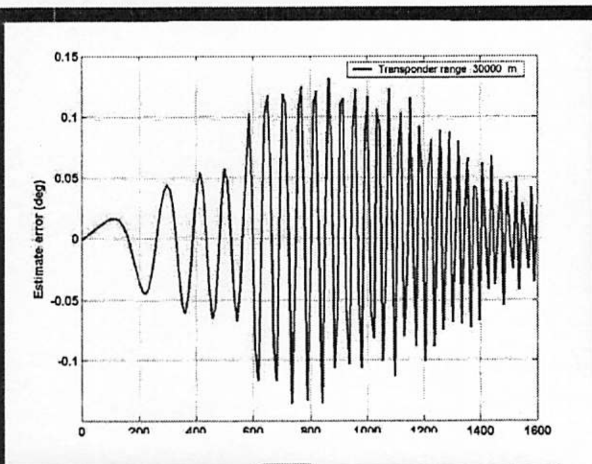




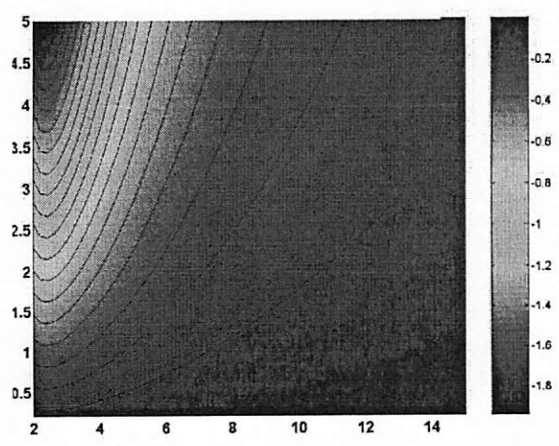
Monopulse example







- First step for design curves



- Maximum error in monopulse curves

Summary and final words

- **Overview of capabilities at TNO with respect to wind turbines and radar.**
- **Wind turbines and obstacles do hamper radar detection, severity needs to be assessed.**

- **Not treated:**
  - Design curves
  - Interaction between turbines (next to each other and behind each other)
  - Coherent radar and modulation effects
  - Results for ghost targets.

The Impacts of Wind Turbines on UK Civil Aviation - Constraints and Mitigation

Ian Fletcher – March 2005

1 The PSR problem

The principle concern of civil aerodromes in considering the affects of wind farms is the generation of false returns or clutter. Generally, in the interests of safety, an air traffic controller must necessarily regard persistent clutter as an aircraft and vector all air traffic around it by the relevant separation distance of 3 to 5 nm.

False returns

Both the tower and the rotor of a wind turbine may be detected by PSR. The tower is stationary and so can be processed or filtered out in the same as any other stationary structure such as buildings. It is the nature and variability of returns from the rotating rotor which present a special case. Because the rotor blades have velocity they can generate a Doppler shift and consequently become difficult to distinguish from aircraft. The rotating rotor of an individual wind turbine will only produce a return occasionally, perhaps one in 6 sweeps. Over a wind farm of many turbines, different turbines can paint (produce a return on the radar screen) on each sweep and generate a twinkling effect. The return from an individual turbine will always appear in the same place. False returns on PSR from wind turbines are a source of radar 'clutter', the importance of which is dependent upon the level and nature of activity in the sector affected.

Shadow

Shadowing is the masking of radar returns from aircraft behind a wind turbine. Depending on the position of the turbine with respect to the radar, shadow is generally only a concern where the ATS provider is concerned with aircraft operating at low altitude behind the wind turbine. It is therefore generally of greater concern to the Ministry of Defence Aerial Surveillance and Control System (ASACS) radars than to civil air traffic control radars.

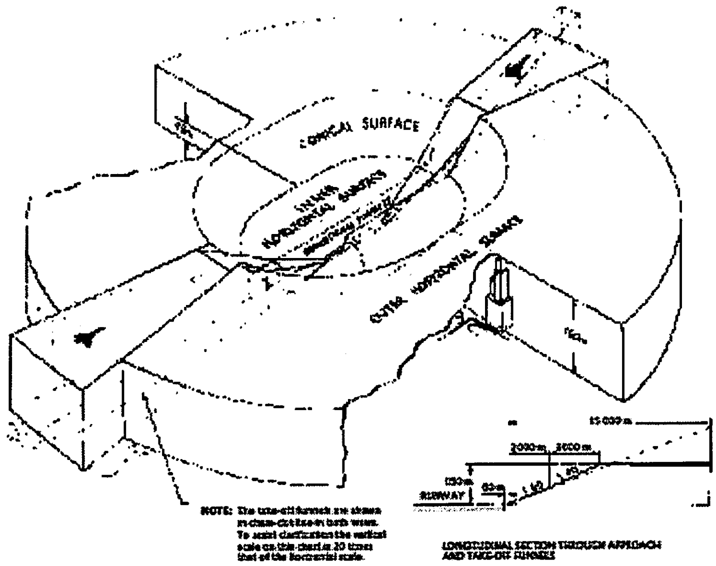
Automatic tracking

In the case of individual wind turbines any return will remain stationary between radar sweeps and no track will be generated. In the case of wind farms it is possible for returns on successive sweeps to come from different wind turbines. This can be interpreted by plot extraction processing as a moving target and a track can be initiated. Track non-initiation windows will eliminate the generation of false tracks from a wind farm. The value of setting up non-initiation windows depends upon the use of the local airspace and the cumulative affects of establishing several such areas. There have also been reports that genuine aircraft plots have been temporarily lost whilst an aircraft is flying in the vicinity of a wind farm, subsequently being picked up again.

2 Procedures and Airspace

2.1. Physical safeguarding of licensed aerodromes

The CAA publication CAP 168 provides details of the physical safeguarding characteristics of licensed aerodromes. Surfaces are defined around the runways as illustrated below. Wind turbines which penetrate these surfaces then constitute physical obstacles. Such obstacles are not rare and whilst it is best to avoid infringing safeguarding surfaces it does not automatically mean that a wind farm can not be built. This will depend on the specific location and the use of the airspace.



Obstacle limitation surfaces for an instrument runway where the main runway is 1800 m or more in length

The take off and Climb surfaces (TOCS) extend as far as 15km, as does the outer horizontal surface, both dependent upon the physical characteristics of the runway.

2.2. Planning – safeguarding maps

All safeguarding measures for wind farm developments, including the effects on radars and navaids, should be considered by aerodromes, out to a distance of 30kms radius or 34 kms where there is an ILS approach. In practice the CAA only ask developers to consult with civil aerodromes out to a radius of 30 kms from proposed wind farm sites

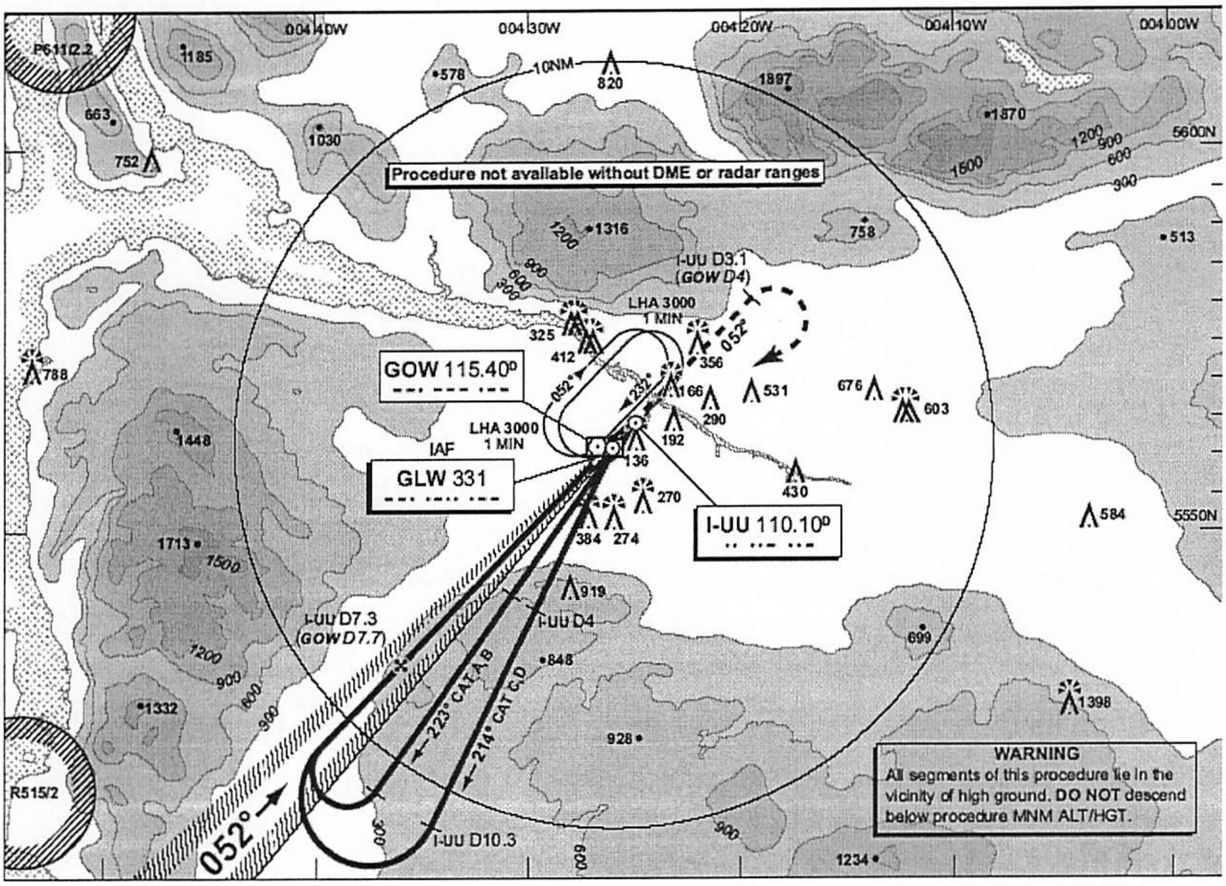
Aerodromes with their ATS providers are responsible for the technical safeguarding of all the radio sites for which they hold approvals under the ANO. Where an aerodrome is concerned about the potential impacts of a proposed wind farm, the onus is on both the aerodrome licensee and the developer to liaise in order to address those concerns. It is reasonable to request that a wind farm developer co-operate in providing evidence that the safety of the ATS provision will not be compromised or degraded by a wind farm development.

Aerodromes, whether licensed or unlicensed, are advised to lodge safeguarding maps with local planning authorities. Such maps are usually physical safeguarding maps and indicate the height of buildings in each square kilometre that will infringe upon their safeguarding surfaces.

3 Procedures and Airspace

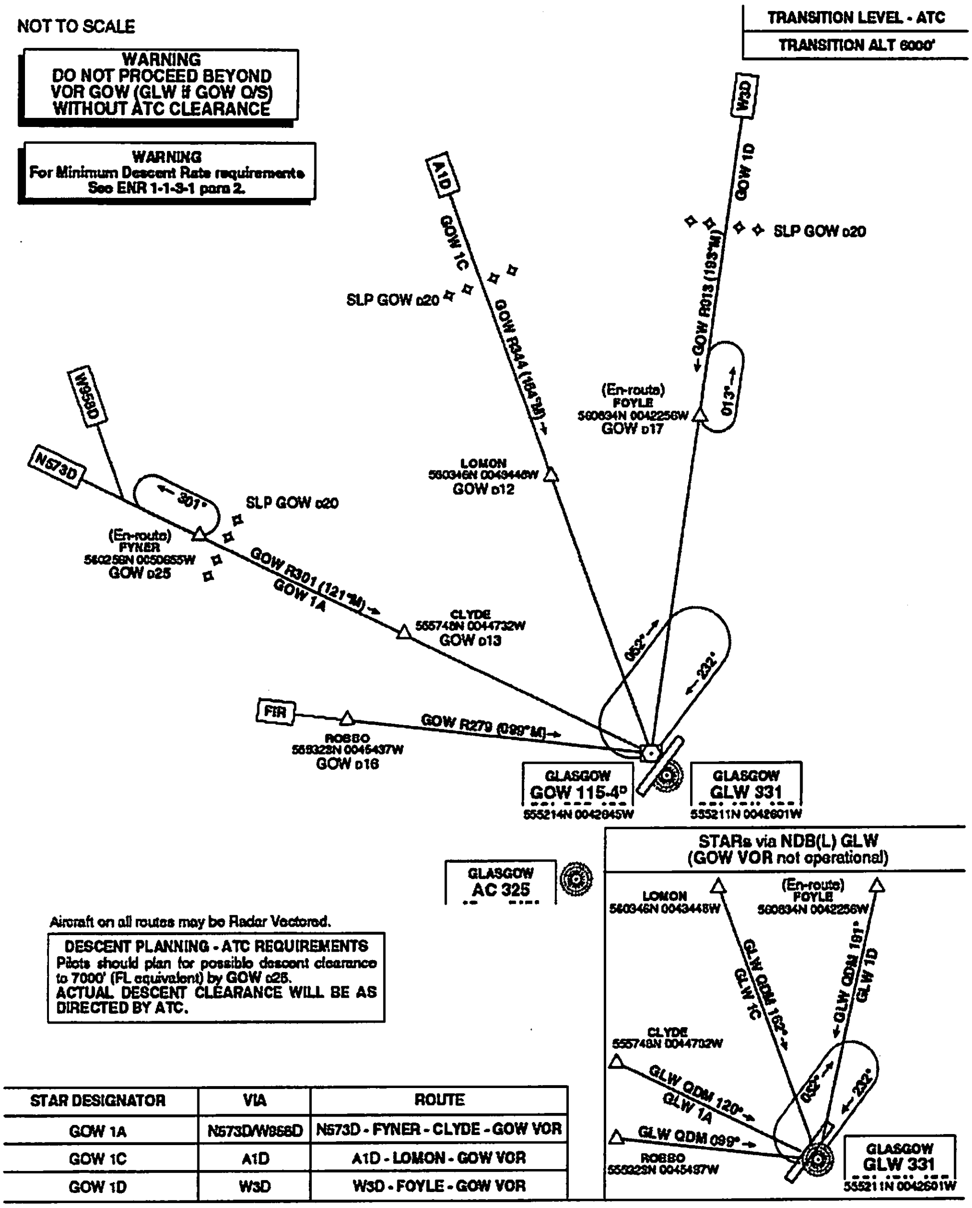
3.1. Final approaches

The below map shows a typical Instrument approach procedure, in this case for Glasgow Airport. It is important to have a clear radar picture where the aircraft will be vectored around the aerodrome and wind farms should avoid such areas.



3.2. SIDS, STARS and Reality

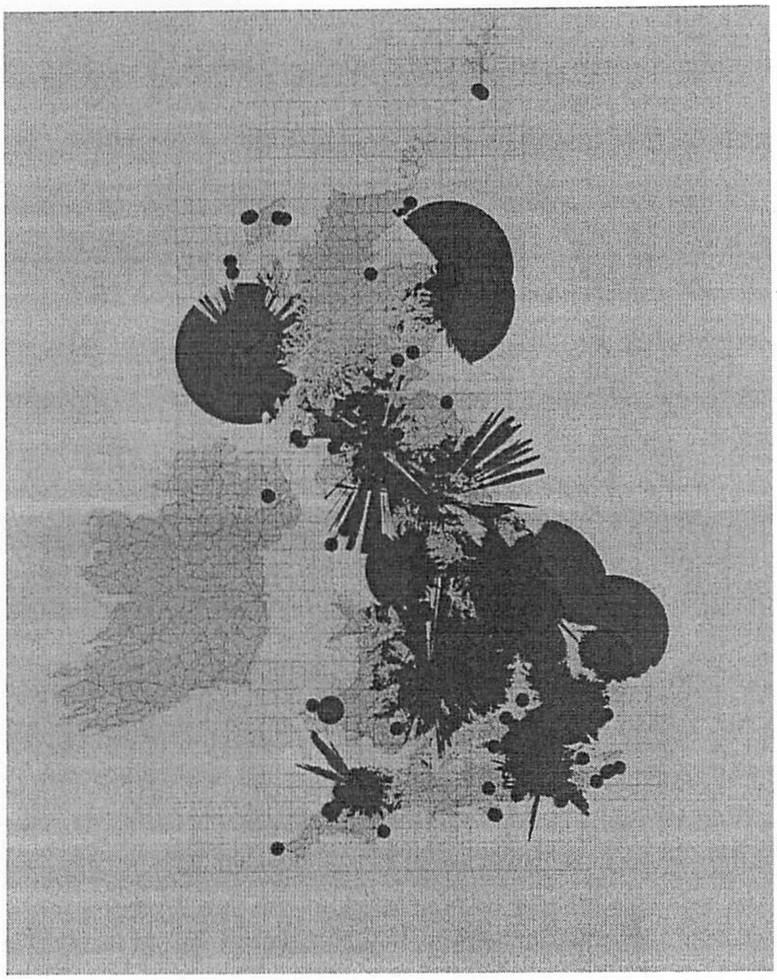
In addition to the approach procedures aerodromes also publish Standard Instrument Arrivals (STARs) and Standard Instrument departures (SIDs). This is illustrated below in a Glasgow chart of Standard Arrivals via VOR. In some cases these provide a useful indication of the routing of aircraft around aerodromes. However it is common practice to move aircraft freely within the aerodromes control area in order to maintain the required radar separation and stacking distances. This results in much larger tracts of airspace requiring reliable radar coverage and the maintenance of a clutter free picture.



STAR DESIGNATOR	VIA	ROUTE
GOW 1A	N573D/W958D	N573D - FYNER - CLYDE - GOW VOR
GOW 1C	A1D	A1D - LOMON - GOW VOR
GOW 1D	W3D	W3D - FOYLE - GOW VOR

4 NATS

The en-route Air Traffic Control service, provided by the NATS is based on both primary and secondary radar. They have now issued maps to show the areas of the country that are visible to their primary radar. Where a proposed wind farm falls within the areas indicated they may object, otherwise they will not. The map below shows the NATS technical safeguarding map against wind turbines of tip height 120m.



5 Mitigation options

The following lists possible PSR mitigation options, ranging from the simple redesign of the wind farm in order reduce radar visibility, to the electronic removal of returns from the radar with improved radar processing software.

a. Site design
b. Accepting clutter (reduced service)
c. Modifying procedures
d. Improving the radar picture (upgrade, Using SSR only)
e. Regulation changes
f. Removing radar returns
    i. RAG maps
    ii. Additional sensors
    iii. ADT
    iv. Stealth blades

6 SSR

Secondary Surveillance Radar presents a much smaller constraint on wind development than PSR. Wind turbines are unlikely to cause significant disruptions to SSR unless they are constructed in close proximity to the radar. Whilst the safe distance has not been established it is generally recognised that unwanted echoes on

PSR is a much more likely issue and receives more attention. With the current conservative position, required in the absence of scientific proof, it is reasonable to assume that wind turbines at a range of over 15 kms do not generally create much concern, whilst those closer than 10 kms are likely to create concern and so require more thorough evaluation

Reflection

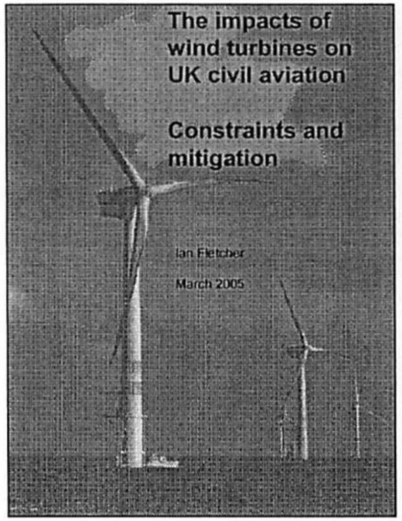
If a wind turbine reflects an aircraft transponder signal at sufficient magnitude, the receiving antenna may receive an apparent SSR reply. This in turn may result in a ghost return on the operators display in the direction of the reflecting object.

Corruption

It is possible for the aircraft return signal to be corrupted by a wind turbine which is in front of an aircraft, almost on the same bearing. Where the deflected signal is of similar magnitude to the aircraft's direct signal, the slightly different path length can corrupt the pulse coding making the reply uninterpretable.

7 ILS

The safeguarding situation for ILS, and associated systems, is fundamentally different to that for PSR and SSR, as comprehensive technical modelling solutions have been developed to allow an ILS operator to evaluate the effects of complex structures (such as tower cranes) prior to installation. Such modelling should be adaptable to address the effects of wind turbines on ILS. Any interference effects will be seen by aircraft rather than the ground system. CAP670 provides guidelines (Gen02 4.3) and example safeguarding areas which should be applied in the absence of data from other sources. The safeguarded areas provided, for all categories of ILS localiser, extend up to 1.5 km from the runway threshold. A wind turbine sited further away should not interfere with the ILS system. Note that ILS equipment is variable and the manufacturer should be referred to for accurate safeguarding frame sizes. It is likely that the manufacturer may specify a smaller area to be safeguarded.



Contents

1. The PSR problem
2. Procedures and Airspace
3. The UK planning system
4. NATS
5. Mitigation options
6. SSR
7. ILS

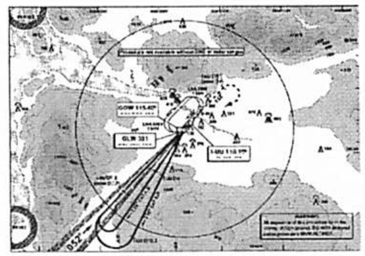
Wind Business

The PSR problem

- False Returns is the principle problem
- Also tracking errors
  - Generation of false tracks
  - Loss of genuine tracks
- Shadow not an issue

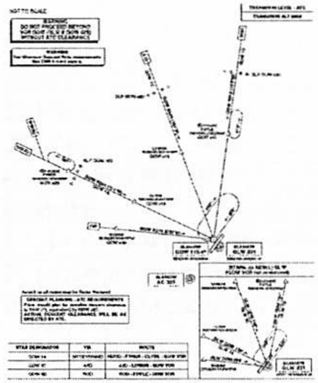
Wind Business

Procedures and Airspace



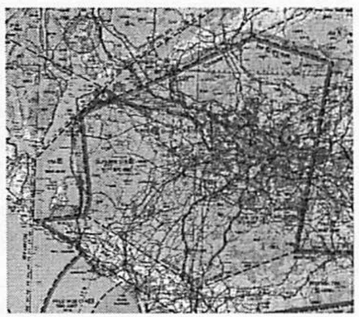
Wind Business

Procedures and Airspace



Wind Business

Procedures and Airspace



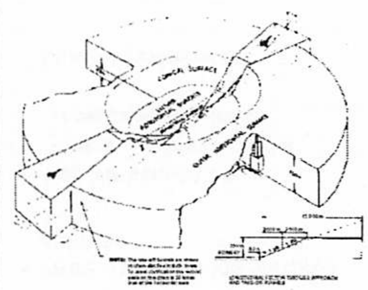
Wind Business

The UK Planning System

- The DAP will ask developers to consult with aerodromes within 30km
- Aerodromes should lodge safeguarding maps

Wind Business

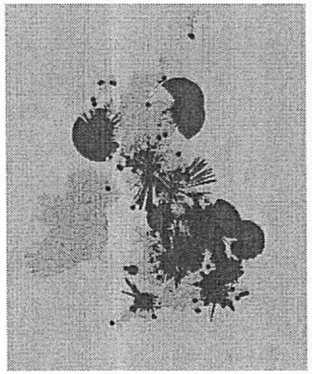
Physical safeguarding



Obstacle limitation surfaces for an instrument runway where the main runway is 1800 m or more in length

Wind Business

NATS En-Route



Wind Business

SSR

- Effects of WTs
  - Reflection
  - Corruption
- Mitigation
  - Keep 10km plus away

Wind Business

Mitigation Options

- Site design
- Accepting clutter (reduced service)
- Modifying procedures
- Improving the radar picture (upgrade, Using SSR only)
- Removing radar returns
  - RAG maps
  - Additional sensors
  - ADT
  - Stealth blades
- Regulation changes

Wind Business

ILS

- Interference effects will be seen by aircraft rather than the ground system
- Comprehensive technical modelling solutions have been developed
- Safeguarded areas provided, for all categories of ILS localiser, extend up to 1.5 km from the runway threshold

Wind Business

QinetiQ Proprietary

Radar and wind turbine blades
The materials solution

Dr Steve Appleton

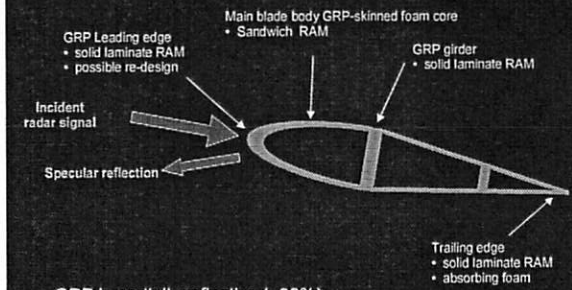
RF Materials

QinetiQ

QinetiQ

QinetiQ Proprietary

Why turbines are a problem



- GRP is partially reflective (~38%)
- RCS of cylinder is large, proportional to Length^2
- Blades, tower and nacelle contribute to RCS

QinetiQ

Content

Introducing the problem

Results of previous DTI-supported projects

The proposed new project – options for discussion

QinetiQ

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QinetiQ understanding of turbine RCS

- QinetiQ have completed 2 separate projects under DTI support, both relating to the radar problem of wind turbines.
  - *"Wind Farms Impact on Radar Aviation Interests"*
    - Building on previous RCS prediction expertise, a model was developed that allowed the RCS of a turbine to be predicted as a function of blade yaw and pitch.
    - Predictions were validated by portable RCS measurements of several installed turbines
  - *"Design & Manufacture of Radar Absorbing Wind Turbine Blades"*
    - This project aimed to apply QinetiQ's radar stealth materials expertise to a 34m composite blade made by NOI Scotland
    - All materials found along the blade were considered and a cost-effective, weight-acceptable method for introducing stealth was sought for all materials

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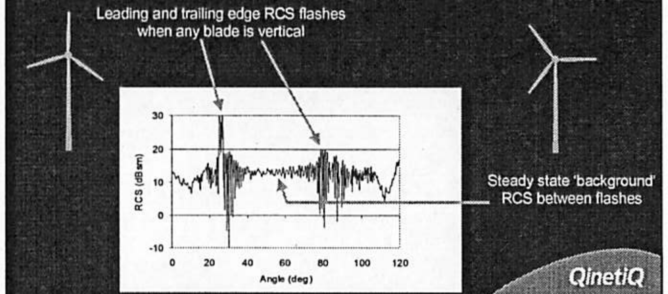
RCS predictions

90° yaw (i.e. blades moving towards and away from the radar) is the most important case for Air Traffic Control (ATC) because it creates the greatest Doppler component



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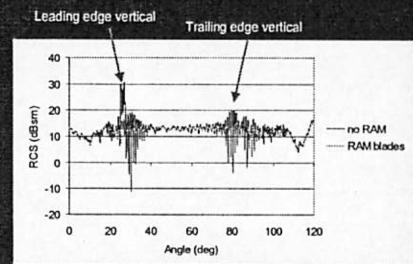
RCS predictions and radar impact modelling

90° yaw / 0° pitch

- blades rotating towards and away from radar
- leading edge pointing directly at radar
- 0dBsm is a typical 'aircraft size'
- RCS peak is reduced from 30dBsm to 15dBsm
- The tower and nacelle are still contributing strongly



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Design & Manufacture of Radar Absorbing Wind Turbine Blades

- DTI-supported project
  - Blade radar cross section (RCS) predictions
    - study based on detailed CAD of 34m blade
    - considered stealthy blades, tower, nacelle
  - Radar system modelling
    - air traffic control 2-3 GHz
    - weather radar 5.6 GHz
    - marine navigation 9 GHz
    - identify benefit of various levels of stealth
  - Manufacture of stealthy blades (RAM), aiming for:
    - small modifications to composite blade
    - little change in manufacturing method
    - no structural detriment

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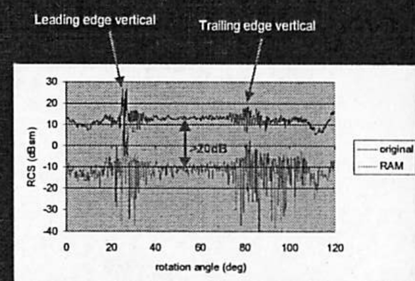
If the whole turbine is treated with RAM, predictions show that the bulk of the RCS spectrum falls below 0dBsm

Only the leading edge spike rises much above 0dBsm



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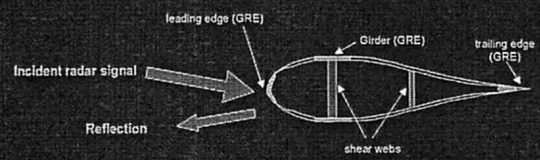
Materials requiring modification (typical)



- Solid glass fibre reinforced epoxy (GRE)
- GRE-skinned lightweight foam core sandwich panels (FS)
- Carbon fibre composites in places, especially for larger turbine blades

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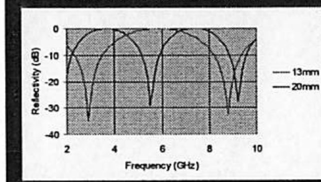
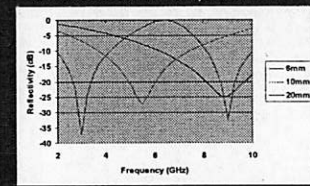
Some simple RAM designs

Solid GRE laminate RAM



GRE/foam sandwich panel RAM



BUT – these predictions are for purely resistive layers in a ¼ wavelength thick layer. Problem is how to make thinner composites work at ~ 3 GHz

- 1/4 wavelength foam thickness for 3 GHz ~ 25mm
- 20mm case just works, but sandwich panels are often thinner than 20mm
- what if we need to go to 2 GHz ?

- SOLUTION – QinetiQ novel interlayers

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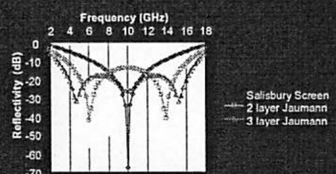
Radar Absorbent Materials (RAM)

Salisbury screen | Jaumann absorber



Jaumann RAM performance v number of layers

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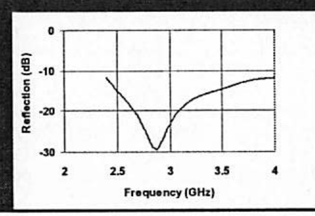
The QinetiQ RAM solution

The QinetiQ approach has been to introduce controlled impedance properties into the current glass cloths, to electrically tune even thin (compared to wavelength) composites

- The lossy layers are modified versions of current glass cloths
  - composite 'friendly'
  - minimal change to process (RIFT, wet layup, prepreg are all possible)
  - little or no change in mechanical properties
  - added weight < 0.25% of existing composite structure



Measured performance for a GRE/foam/GRE sandwich panel

-10dB = 10% reflection
-20dB = 1% reflection
-30dB = 0.1% reflection

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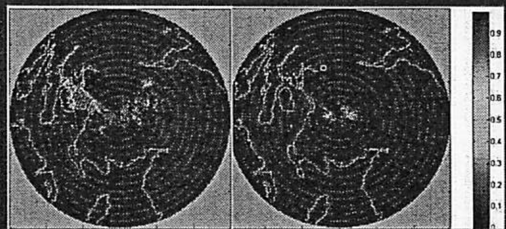
- Impact of RAM treatment on Probability of detection of turbine
  - Models use radar operational parameters and terrain data to calculate propagation and detection at any azimuth position
- Hare Hill site near Prestwick Airport, median RCS



Standard turbine RAM turbine

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Proposed new project

- RCS prediction studies – identify RAM schemes
- Re-design of Vestas blades and nacelle
- RAM trial
  - lightweight, temporary RAM
  - confirmation of predictions

    decision point
- Produce RAM blades and nacelle cover
- Produce tower RAM
- Install stealthy turbine
- Radar measurements – airport and QinetiQ radar (MPR)

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What now ?

The QinetiQ studies have shown that it is feasible to reduce the RCS of wind turbines, using composite RAM, to levels less than that of small aircraft. It appears hopeful that ATC and other radars could safely discriminate such stealthy turbines from real aircraft.

However, models can never fully replicate reality and we need to demonstrate the predicted RCS reductions and their benefits in radar detection reduction

QinetiQ, Vestas and Scottish Power have formed a consortium who wish to quantify the benefits of stealthy turbines.

The consortium recently submitted a proposal to DTI for a supported project, and have been advised that an Offer Letter will be issued in the next few days (subject to final scrutiny of costs by DTI)

QinetiQ

Questions?

QinetiQ

Saab R&D

IEA Radar, Radio & Wind Turbines Meeting
London, March 17-18, 2005

Pontus Nordin
Product Engineering
Saab Aerosystems

Outline

- Message
- The Challenge
- The Opportunity
- Saab in brief
- Saab products and systems
- Saab LO Technologies
- Saab Wind Power Activities
- Pilot study SAV-SPEC 2004,
  "Specification of RCS requirements for wind turbines"
- Proposed Way Forward

Defence – Aviation – Space

Message

- RCS-reducing hardware treatment can greatly facilitate the deployment of off-shore wind turbine parks in the Baltic Sea and in other locations with similar interest from civil and military organizations
- Saab LO technologies can be tailored, industrialized and applied to wind turbines in order to achieve cost-efficient and relevant RCS reduction, also for WT with carbon fiber blades
- Saab is open for international collaboration

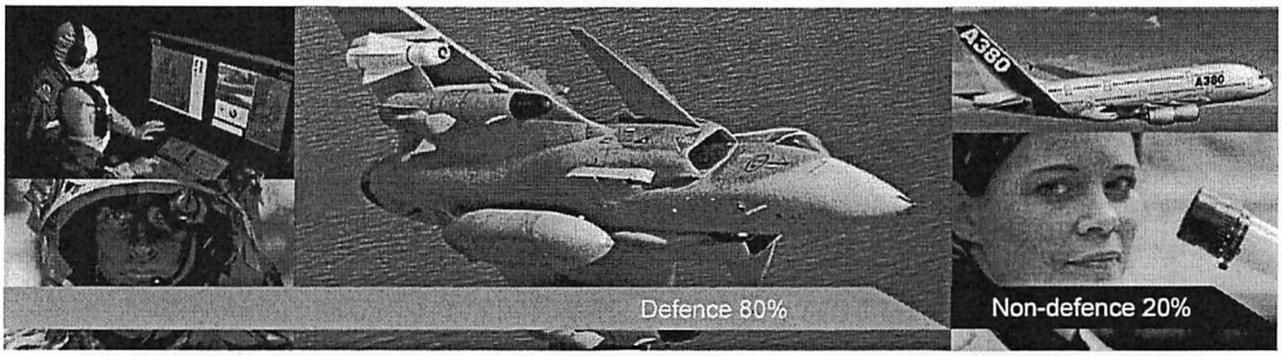
The Challenge

- Today's wind turbines have radar cross sections (RCS) and other electromagnetic characteristics which may prevent their deployment in areas of military interest and/or proximity to radar & radio installations
- Software solutions such as radar filters and intelligent processing of multiple sensor data exist and can be developed further but, based on Saab studies, turbine low observable (LO) treatment is needed for sufficient alleviation of the radar and radio interference problem

The Opportunity

- Available LO technologies can be tailored, industrialized and applied to new generation wind turbines, thereby facilitating their deployment in windy areas subjected to restrictions due to radar & radio
- These technologies, incl coatings and minor structural modifications, have sufficient RCS-reducing effect to solve the radar and radio interference problem for the majority of expected WT deployment in critical locations, also for WT with carbon fiber blades
- Recent value analysis shows a realistic projected cost level for relevant LO treatment of wind turbines

Saab in brief



	2004	2003
Sales SEK m	17,848	17,250
Operating income SEK m	1,567	1,293
Operating margin %	9.3	7.5
Number of employees	11,939	13,316

2004 figures

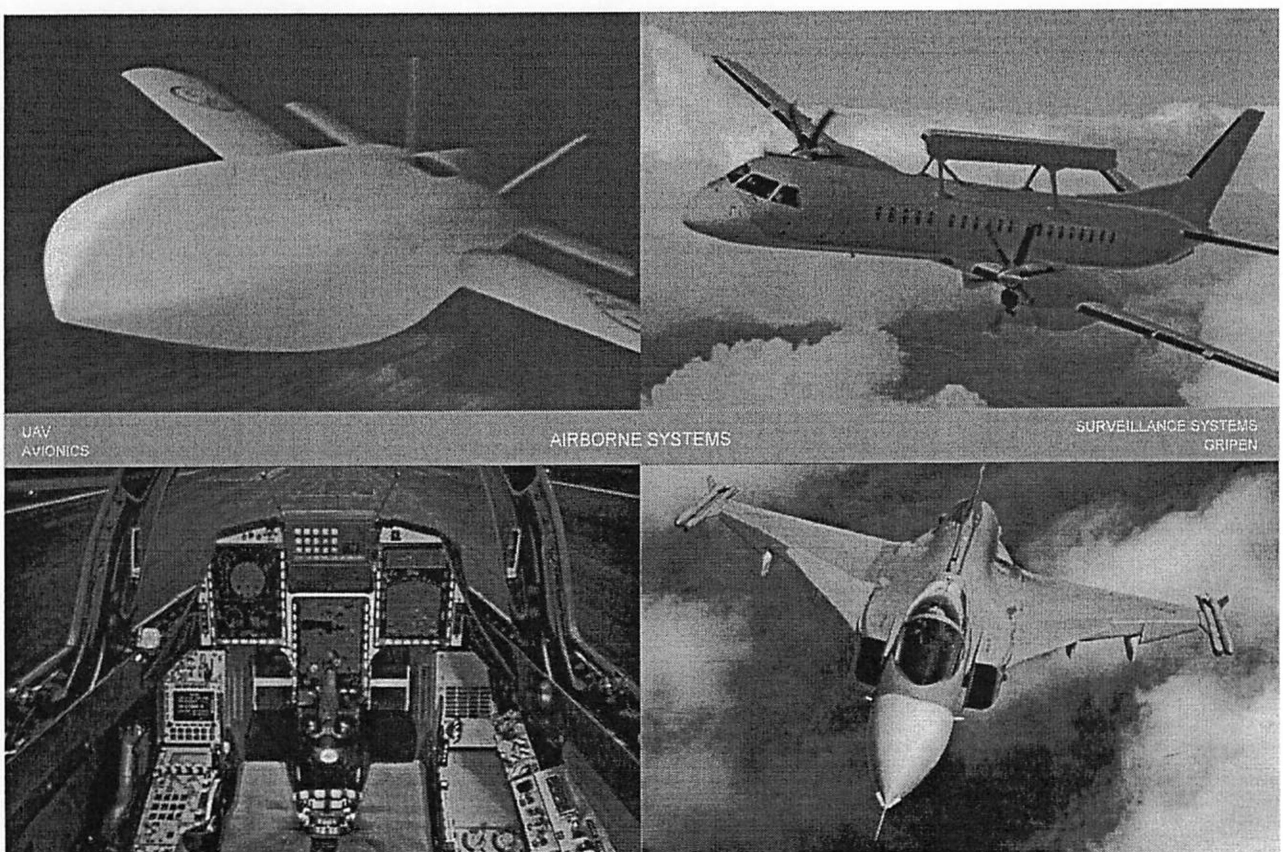
Business concept

Saab offers broad-based systems solutions, products and services in public security, defense, aviation and space as well as related areas in the global market.

Saab products and systems

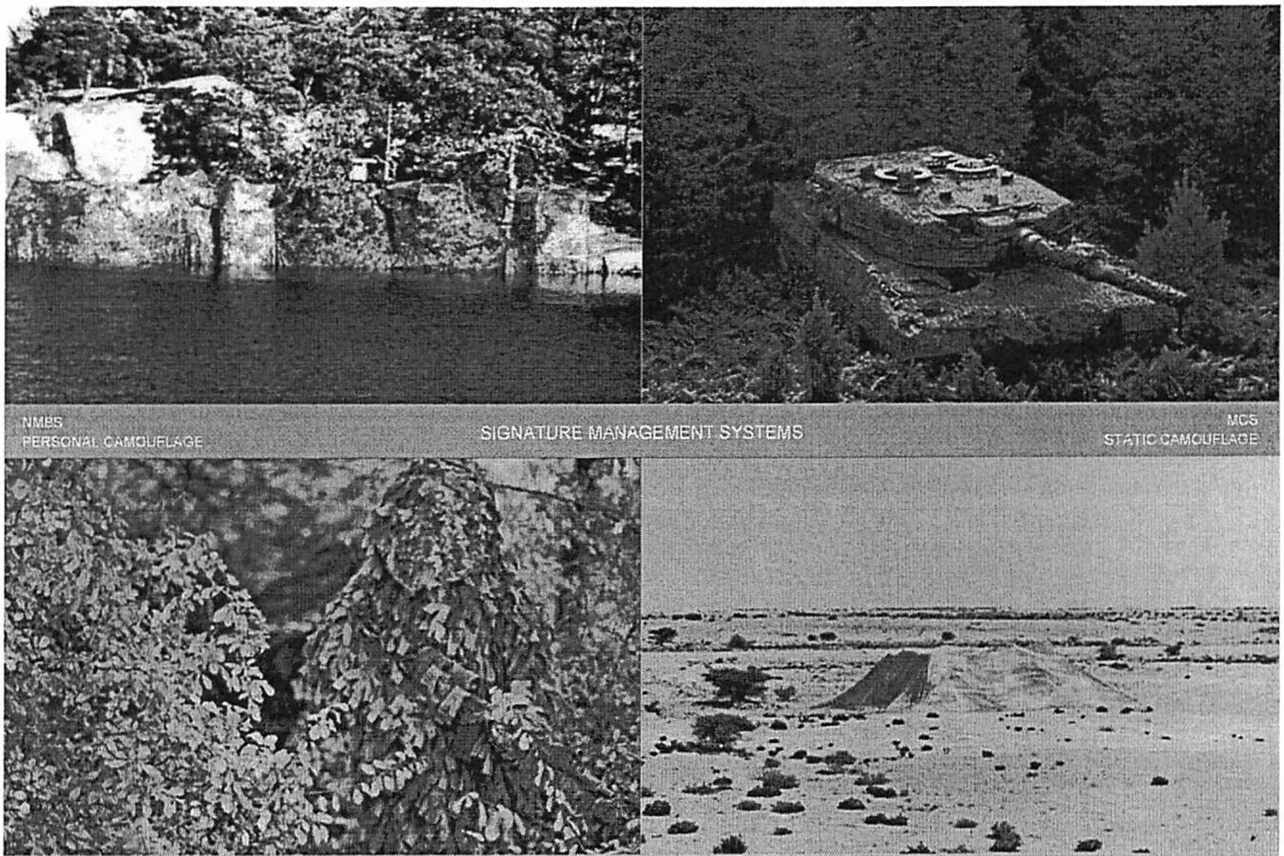
9 SAAB AEROSYSTEMS

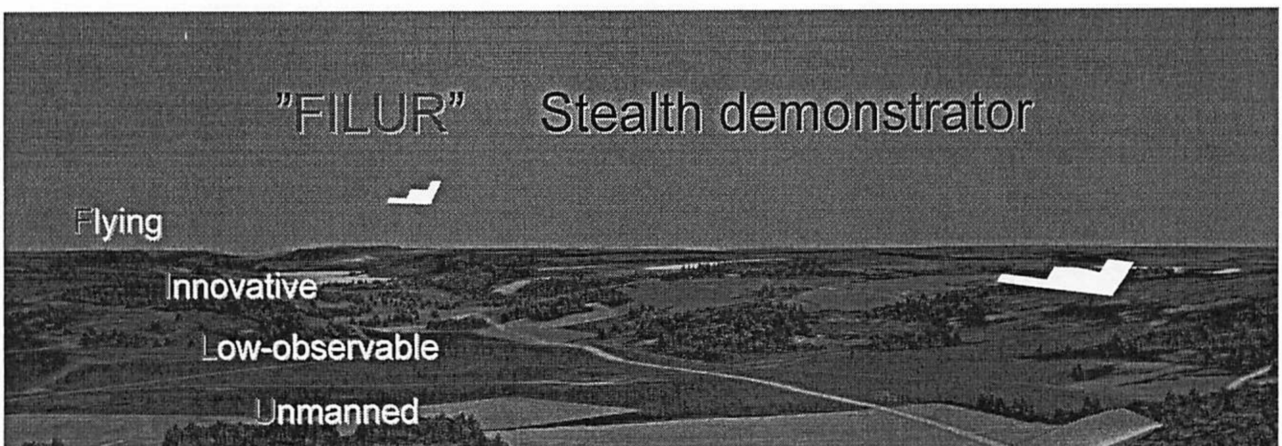
SAAB



10 SAAB AEROSYSTEMS

SAAB


NMBS
PERSONAL CAMOUFLAGE
SIGNATURE MANAGEMENT SYSTEMS
MCS
STATIC CAMOUFLAGE


"FILUR" Stealth demonstrator
Flying
Innovative
Low-observable
Unmanned
Research vehicle
FMV
SAAB

Saab LO Technologies

- Used on land-based objects, naval and aerial vehicles
- Saab Barracuda world leader in military land-based camouflage
- Extensive R&D in software, materials, design & manufacturing
- Important for current and future manned/unmanned air vehicles
- Multi-disciplinary optimization of RCS, aerodynamics, weight, cost
- Unique RAM and RAS technologies with excellent LO performance
- Full scale RCS measurement capabilities
- Suitable for wind turbines

Saab Wind Power Activities

- WT blade technology R&D in the 70ies (carbon fiber blades)
- Extensive composite blade studies 2000 - 2002 (carbon fiber)
- New design and manufacturing technologies for WT blades
- Understanding of electromagnetic compatibility issues, incl radar, visual and acoustics
- Proposed R&D and full scale demonstration of reduced RCS, visual and acoustic signatures based on development of available technology
- Pilot study SAV-SPEC 2004 financed by the Swedish Energy Agency (STEM) "Specification of RCS requirements for wind turbines"

Saab SAV-SPEC Results

- Wind turbine RCS and signal-to-noise calculated for 2-3 MW installations
- Very large RCS from individual wind turbines
- RCS contribution from WT towers can be significant
- Larger WT and/or grouping in farms will increase the RCS problem
- Proposed RCS-reducing treatment includes WT blades, nacelles and towers, possibly in combination with software solutions
- Parametric studies showed that proposed RCS-reducing hardware treatment can result in acceptable radar cross sections

Saab SAV-SPEC Results, cont

- Stand-alone software solutions are considered unacceptable
- Sufficient RCS reduction can be achieved without major redesign
- Sufficient RCS reduction can be achieved within an acceptable cost budget
- Specific RCS-reducing hardware treatment proposed by Saab include;

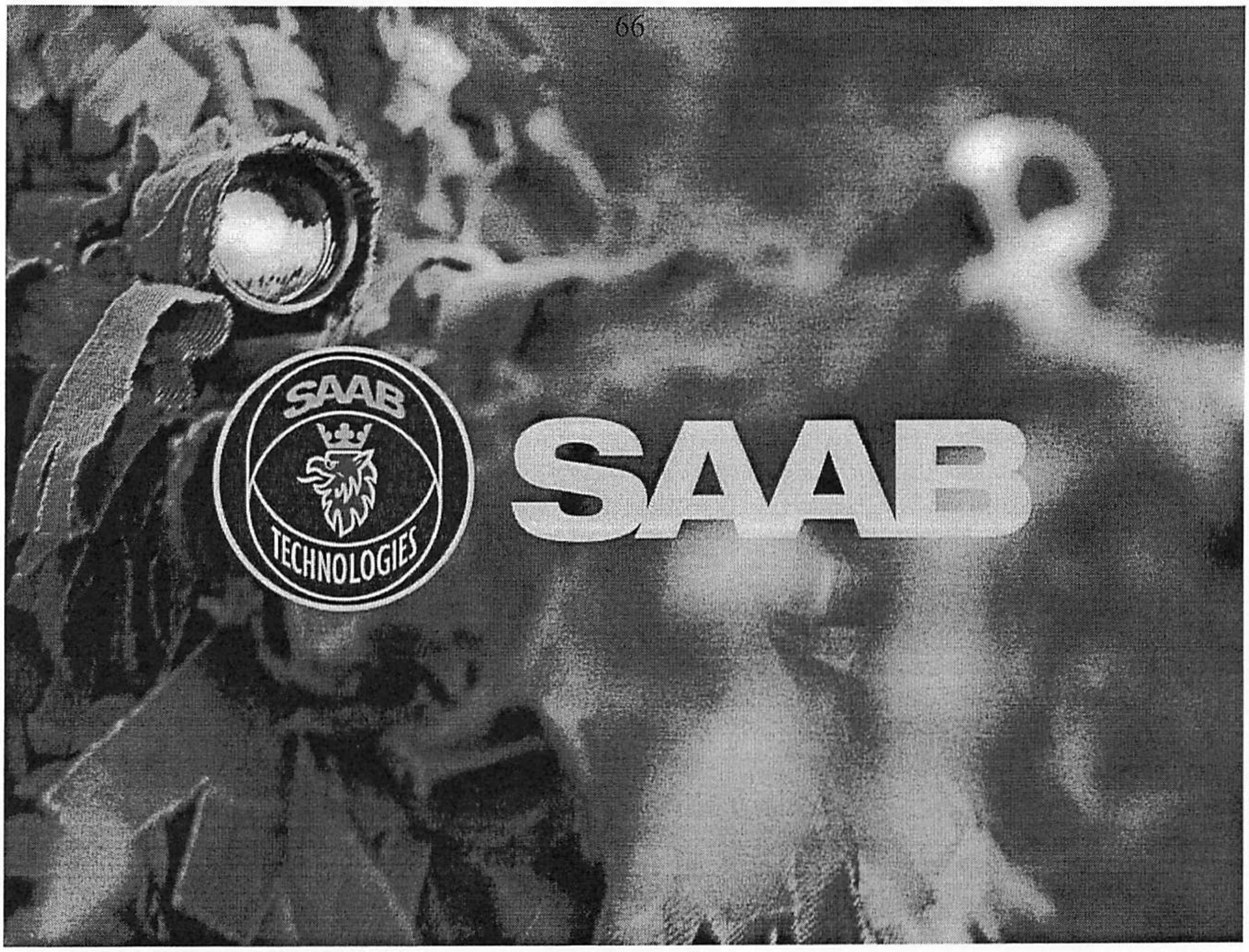
  - coatings
  - no or minor structural design changes
  - limited use of new materials
  - limited use of shaping

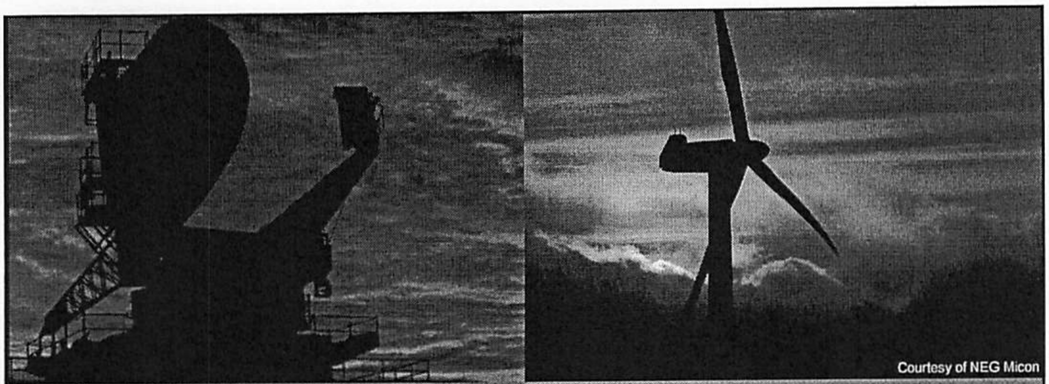
SAV-SPEC Conclusions

- Hardware solutions necessary in order to reduce WT RCS effects to acceptable levels in realistic Baltic Sea simulations
- Software solutions may be needed as a complement
- Saab LO technology a good candidate solution for acceptable WT RCS

Proposed Way Forward

- Demonstration of Saab LO technology applied to WT, including full scale RCS measurements, in collaboration with Swedish authorities
- International collaboration
- Industrialization


SAAB
TECHNOLOGIES
SAAB



Courtesy of NEG Micon

Modelling techniques for assessing impact of wind turbines on radar systems

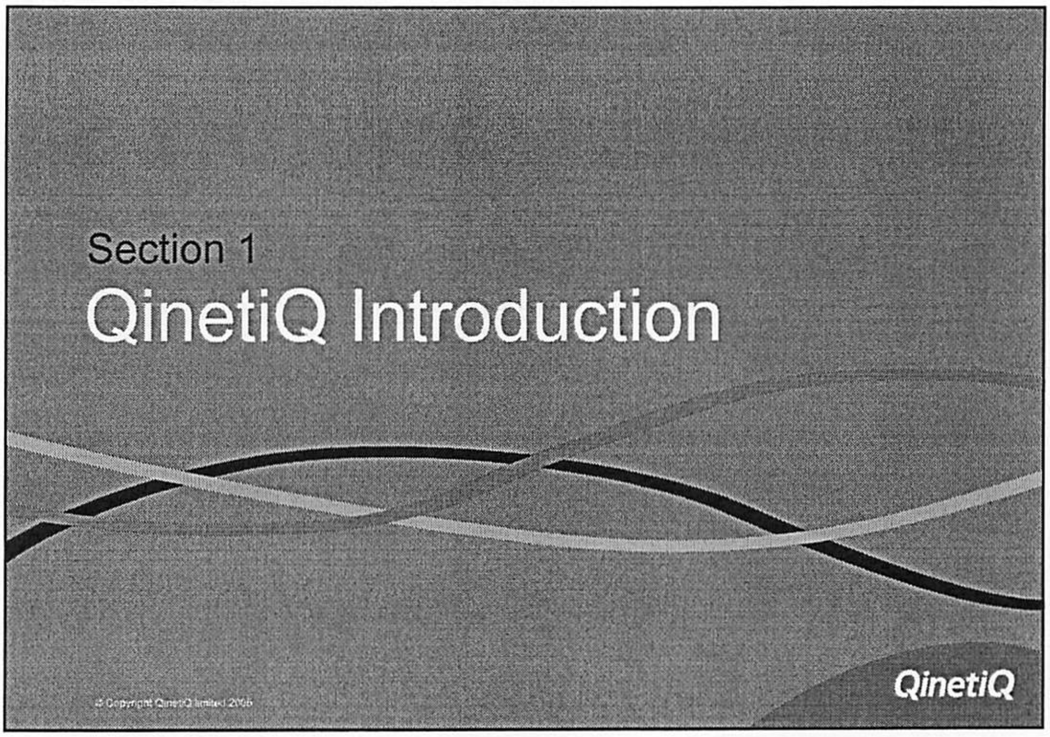
17 March 2005

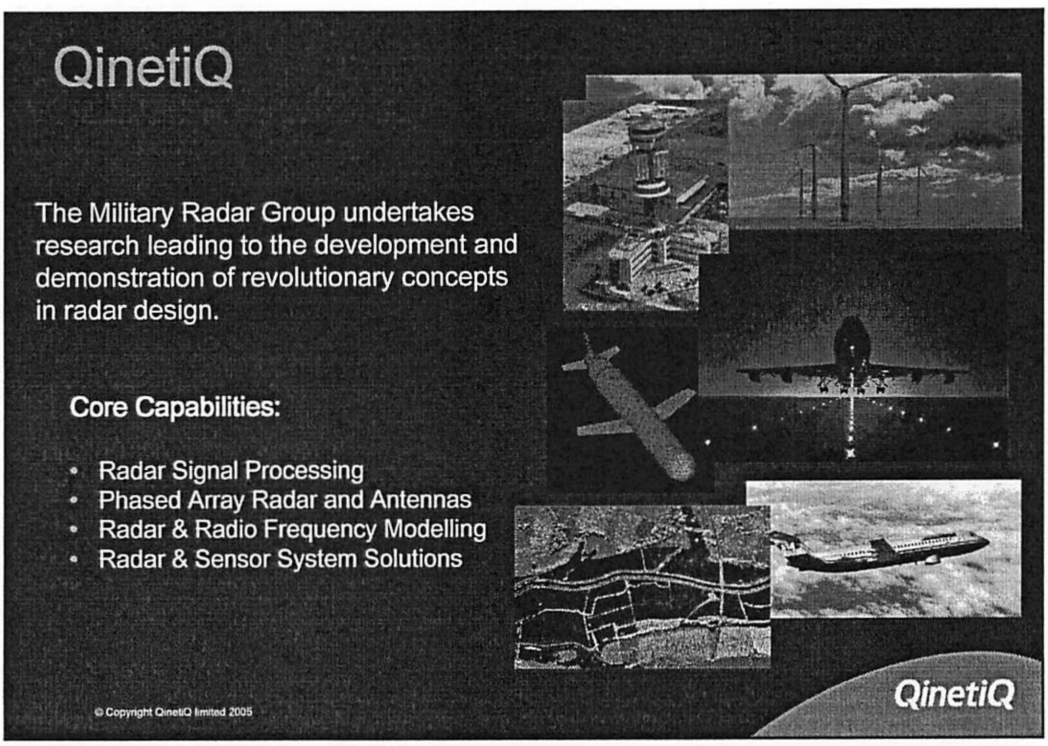
QinetiQ

Contents

1 QinetiQ introduction
2 Radar cross-section modelling
3 Radar impact modelling
4 Radar shadow modelling
5 SSR modelling

QinetiQ


Section 1
QinetiQ Introduction
QinetiQ


QinetiQ
The Military Radar Group undertakes research leading to the development and demonstration of revolutionary concepts in radar design.
Core Capabilities:
• Radar Signal Processing
• Phased Array Radar and Antennas
• Radar & Radio Frequency Modelling
• Radar & Sensor System Solutions
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QinetiQ

Military Radar Group

- The research group at Malvern has been responsible for the development of the UK underpinning radar stealth technology.
- This has involved the development of:
  - Radar signature measurement techniques;
  - Computer modelling of radar signatures;
  - Design and understanding of prototype stealth targets;
  - Development of radar absorbent materials and structures.

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Section 2

Radar cross-section modelling

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Radar cross-section modelling

Prediction techniques

- Codes have been developed for prediction of complex military targets
- Mathematical Methods used are:
  - Physical optics
  - Generalised Theory of Diffraction
- These techniques are valid for large structures such as wind turbines.

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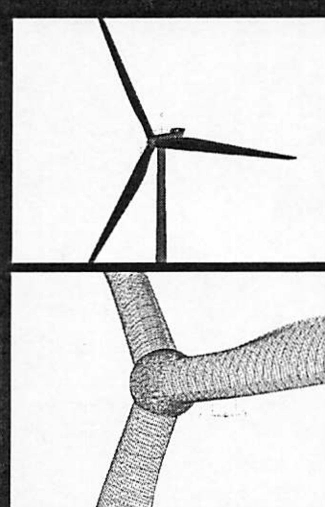
Radar cross-section modelling

Prediction methods

- Input to the RCS modelling tool is a detailed finite element mesh.
  - This is created from a detailed CAD model of the wind turbine in question
- Mesh elements can be given material properties (e.g. fibreglass)
- They can shadow each other
- They can interact via multiple bounce mechanisms
- Can rotate moving blades to collect RCS data for all blade positions



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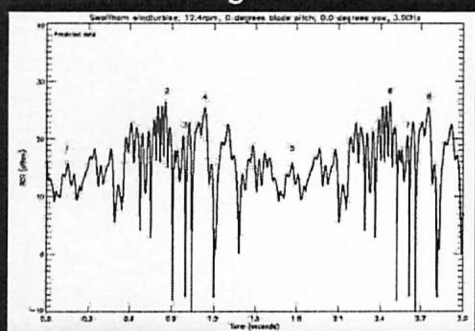
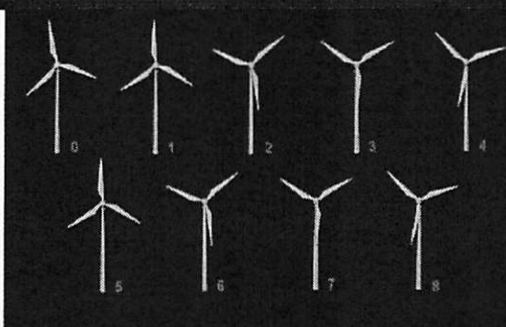
Radar cross-section modelling

Prediction Results

- With the prediction results we can examine the RCS as a function of time (as the rotor rotates), identifying key scattering sources:





RCS for ¾ of a revolution. Turbine viewed from front.

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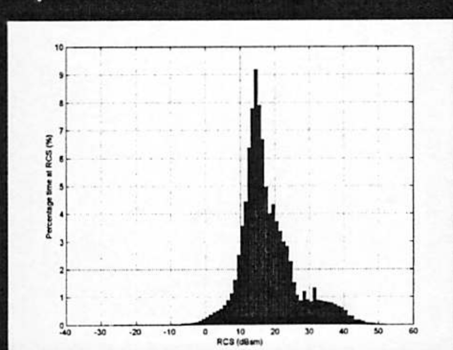
Radar cross-section modelling

Prediction Results

- With data over all turbine yaw angles and rotor positions statistical distributions of turbine scattering are used for impact assessments.



Example histogram of turbine scattering

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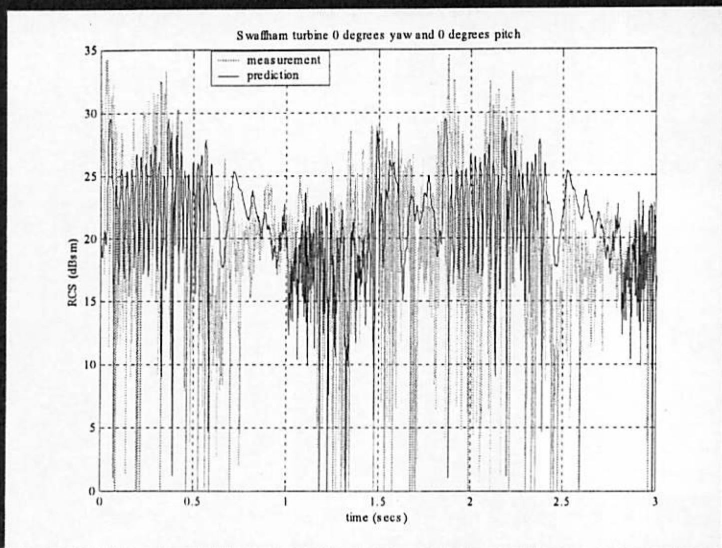
Radar cross-section modelling

RCS Validation



Predictions have been validated by measurements of a turbine.

This was DTI funded research. Level of agreement is sufficient to capture main scattering characteristics

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Section 3

Radar impact modelling

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Radar impact modelling

Propagation modelling

- To assess impact on a radar we can model the propagation over the terrain between radar and turbine
  - Models diffraction and refraction effects
- Mathematical methods used are Fourier Split-step and parabolic equation
- Terrain comes from digital terrain elevation data
- Other features can be added to terrain profiles if required
- Outputs a Pattern Propagation Factor
  - Used to modify scattering magnitudes of turbine in free space

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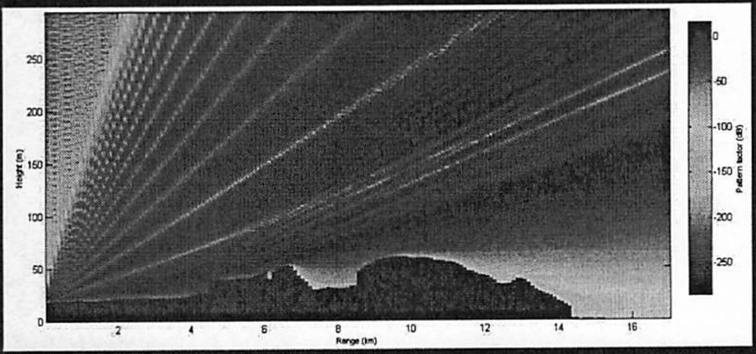
Radar impact modelling

Propagation result examples



Example 2D slice. PPF shown as colour

Cut at turbine range is used to modify turbine scattering

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Radar impact modelling

MTI filter modelling

- Turbine contains stationary and moving parts
  - Primary ATC radar uses MTI to discriminate between aircraft and stationary clutter
- Using RCS data collected vs. time (for a given rotation speed) post-MTI signals from the turbine can be calculated
- Examples shown use a simple triple canceller MTI filter

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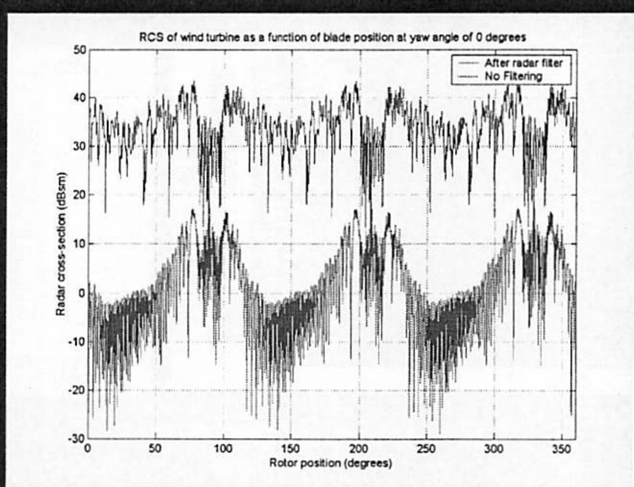
Radar impact modelling

MTI filter modelling examples



Effectiveness of MTI filtering face on to rotor

Large wind turbine

19 rpm

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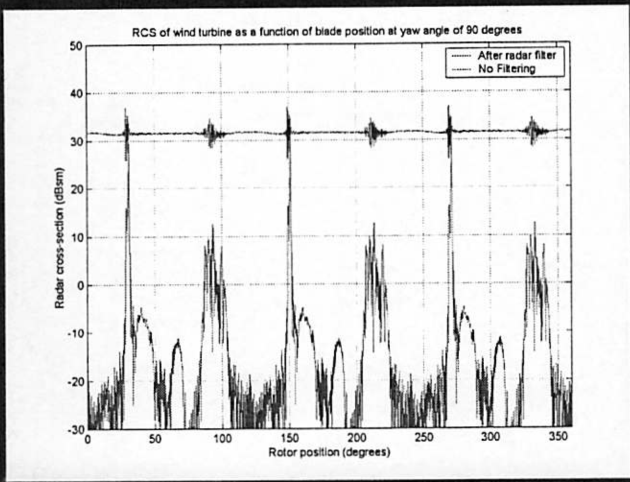
Radar impact modelling

MTI filter modelling examples



Effectiveness of MTI filtering side on to rotor

Large wind turbine

19 rpm

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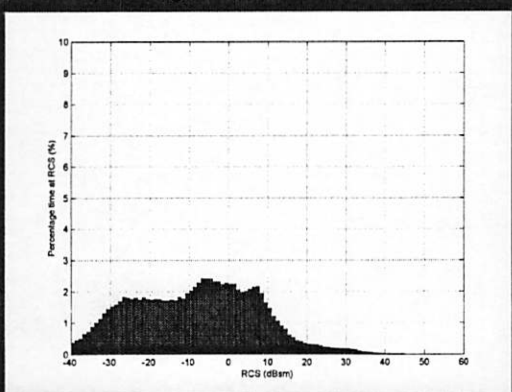
Radar impact modelling

Scattering distribution

- The impact of propagation and MTI can be included into the scattering distribution of the wind turbine



- Wind direction statistics can be used to weight this distribution if wind rose data is available
- This data can be used in radar equation to assess impact

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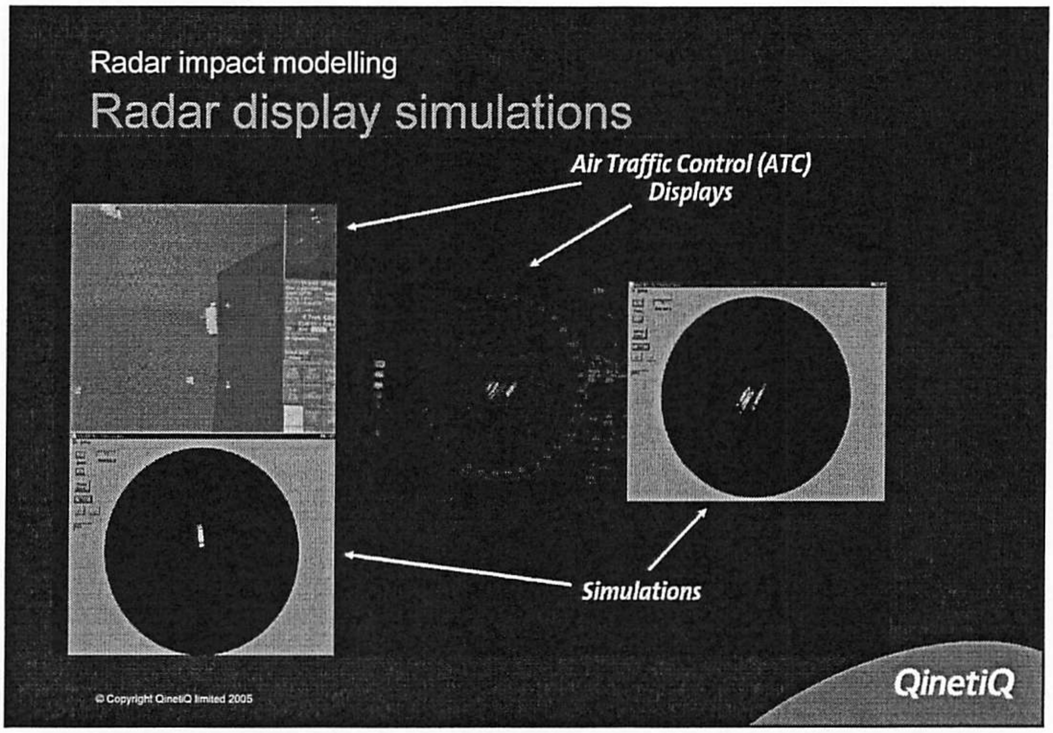
Radar impact modelling
Radar display simulations
Air Traffic Control (ATC) Displays
Simulations
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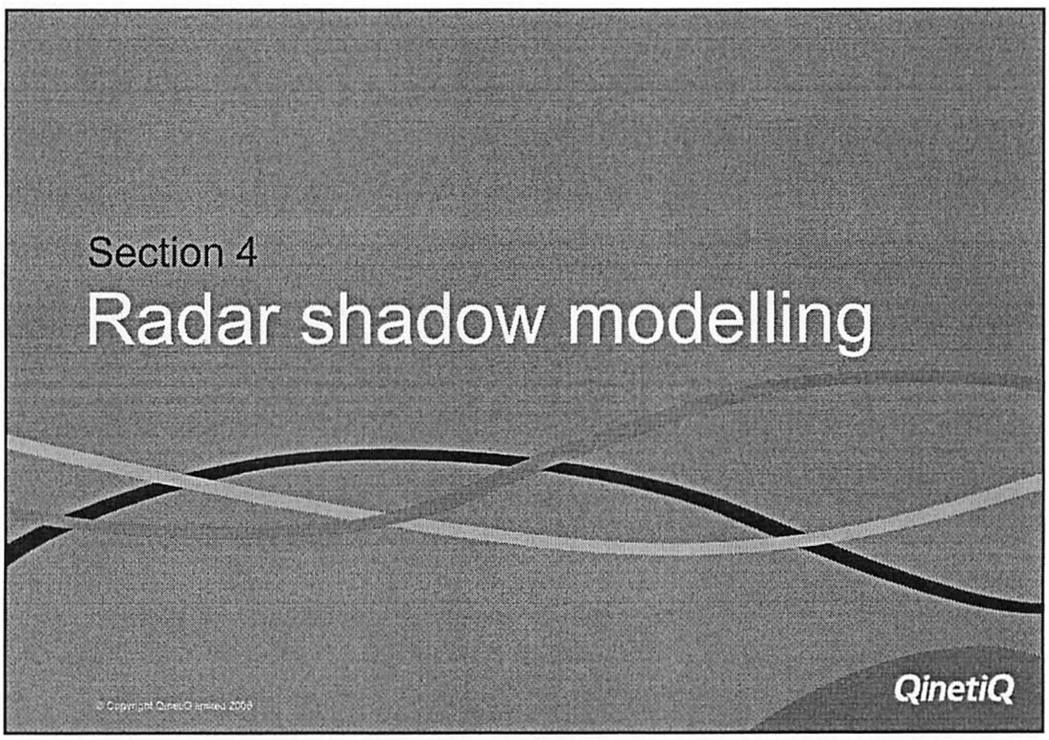
Section 4
Radar shadow modelling
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Radar shadow modelling

Radar shadow

- Typical concern of radar operators is the impact on detection behind the wind farm
  - Especially true for marine radar
- To predict this impact we have created a radar shadow modelling tool
- To make computations tractable we consider the shadow behind the turbine tower, using an infinite cylinder

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Radar shadow modelling

Mathematical methods

- A solution to Maxwell's equations can be found for an infinite cylinder
  - This is a infinite series (Bessel Function)
  - k.a terms are required for convergence (k = wave number, a = radius)
- The solution for one cylinder is used to create shadow effects for an entire farm.
  - Turbines shadowed by other turbines are scaled results based on results from a 2D Method of moments prediction code

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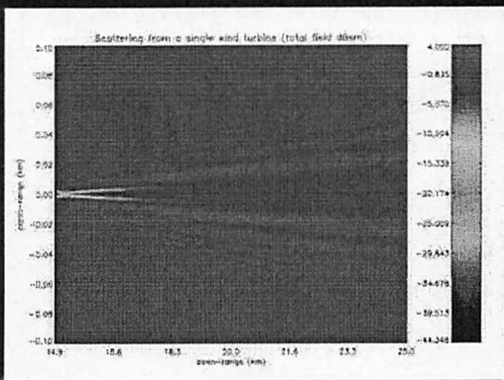
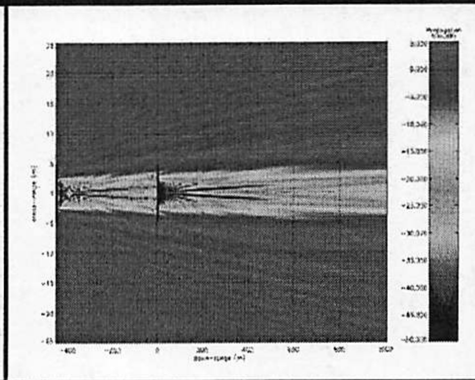
Radar shadow modelling

Example results





One turbine

Two turbines one behind the other

Colour shows shadow depth in decibels

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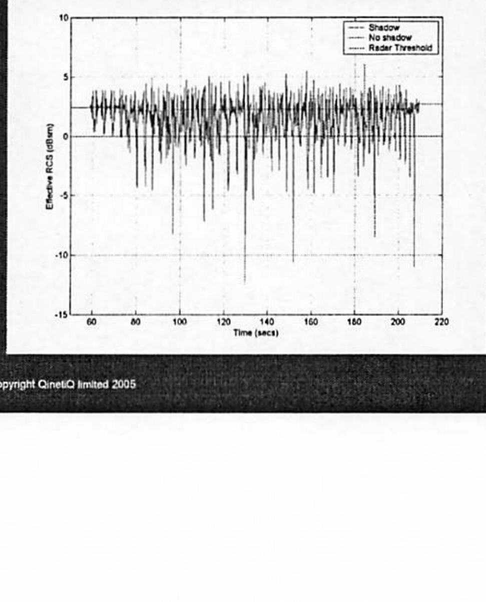
Radar shadow modelling

Assessment process

- By flying or sailing targets though the shadow zone and calculating the effective illumination of the target along the route, impact on detection can be assessed.



Example of impact of shadow zone from a large wind farm on a traversing target

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Radar shadow modelling

Validation

- Done using VHF radios at North Hoyle wind farm
  - Turbine was positioned between transmitter and receiver and impact on radio link margin measured
- For ranges between 500 m and 2 km measurements agreed with predictions to within 1 dB
- Closer than 500 m less shadowing was measured than predicted
  - At 10 m shadow depth was predicted to be ~20 dB
  - Measurements showed no greater than 10 dB of loss

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Section 5

SSR modelling

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SSR Modelling

Interference effects

- Wind turbines (or any other structure) can give rise to false or incorrect MSSR signals by reflecting the up-link or the down-link signal
- The likelihood of this effect is primarily dependent on:
  - Magnitude of the reflected signal
  - Range of the turbine to the radar
  - Range of the aircraft from the turbine
- QinetiQ has created a model to calculate when these effects are likely

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SSR Modelling

Model content

- Modelled MSSR radar systems (requires local settings for each radar)
- Calculated radar cross-section for representative wind turbines – (this time bistatic data sets are collected)
- Local terrain surrounding each radar
- Model uses this data to calculate the reflected power from wind turbines in the areas around an MSSR positions (up link and down link)
- Output is processed and plotted to identify areas where interference from wind turbines is possible

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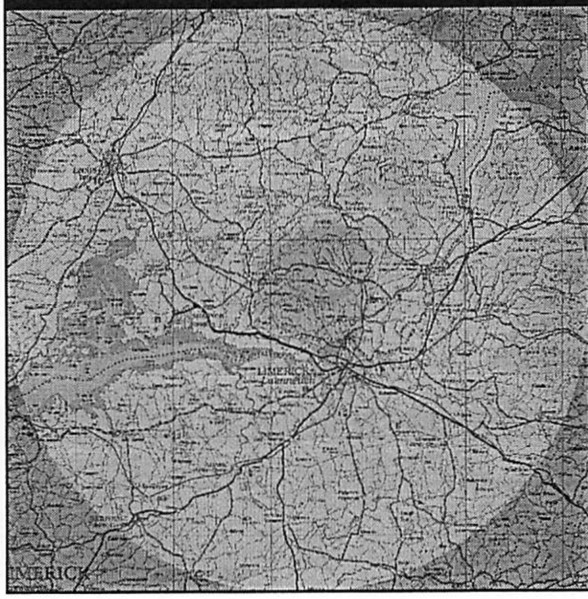
SSR modelling

Example results



- Up-link
- 2MW turbine
- 1200m aircraft altitude
- Worst case target geometry used to generate plots from wind turbine
- Colours indicate likelihood of false plots due to wind turbine reflections

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Section 6
Stealth

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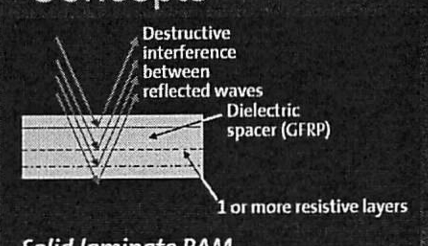
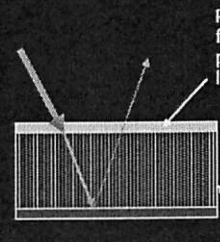
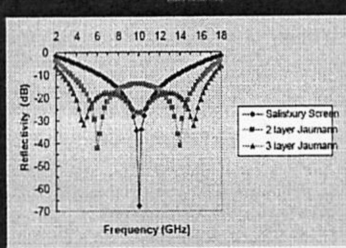
Stealth
Stealth - Radar Absorbing Material (RAM) Concepts



Solid laminate RAM



Sandwich RAM



Example RAM performance

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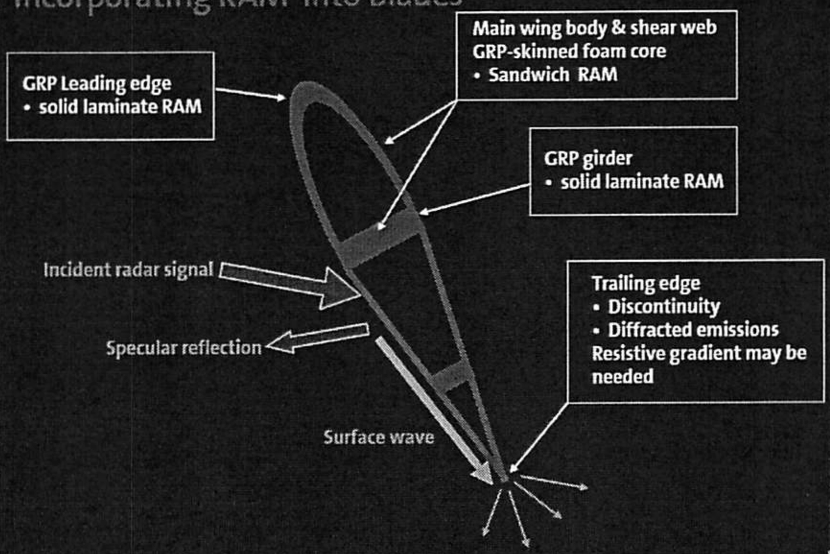
Stealth

Incorporating RAM into Blades



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Type section number or sub-title

Basic bullet point slide

- First level bullet point, do not change the characteristics of bullets and bullet text in any way
- Use the Promote and Demote buttons on the toolbar to change between level settings and bullet points.
  - Second level bullet point
  - Second level bullet point
- First level bullet point, eum iriure dolor in hendrerit in vulputate velit esse molestie

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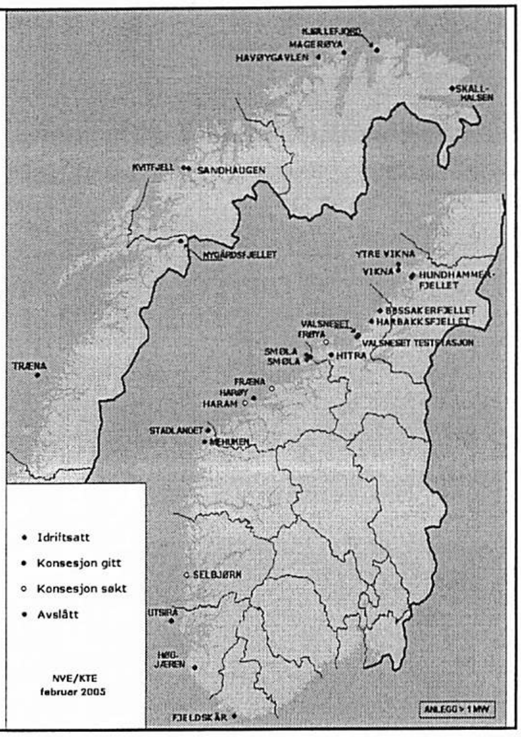
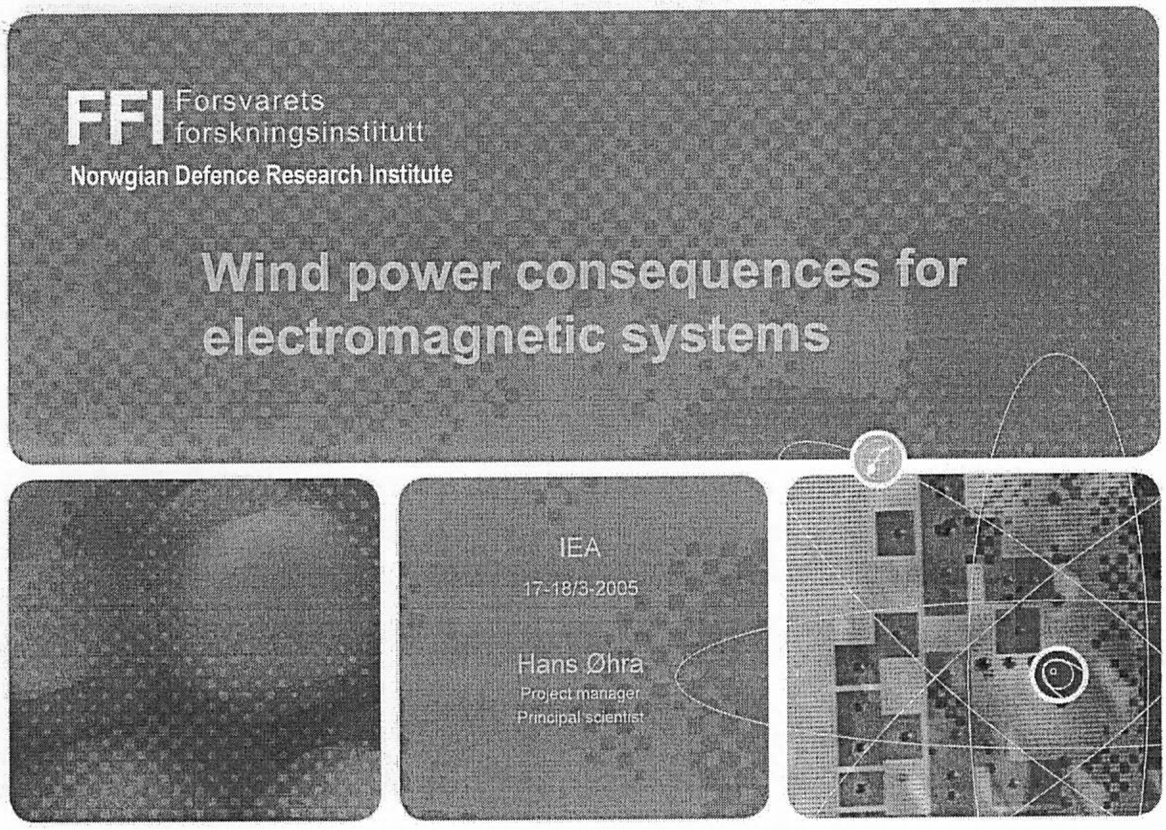
Status wind power in Norway

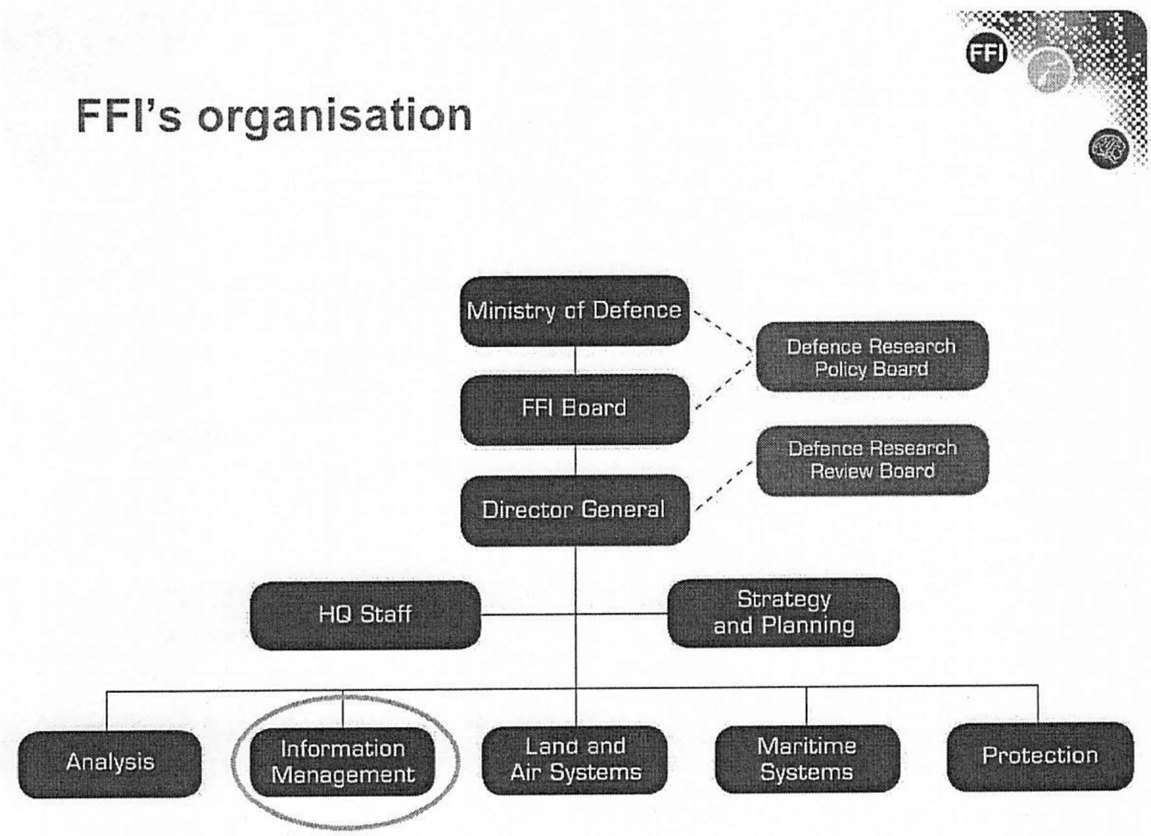
- In operation:
  - 81 turbines (157 MW)
- Under construction:
  - 48 turbines (110 MW)
- With concession – not built:
  - ca. 300 turbines (ca 850 MW)
- Applications:
  - Frøya (200 MW)
  - Selbjørn (40 MW)
  - Fræna (95 MW)
  - Haram (66 MW)
  - Ca. 400 MW
- Possible installations in total:
  - ca. 1500 MW
  - ca. 4,5 TWh/year
- Prenotifications:
  - 40 locations
  - ~6000 MW



Windpower and radar in Norway

- The Norwegian Defence has expressed concern about effects on their infrastructure since 2001.
- Norwegian Water Resources and Energy Directorate (NVE) and the Norwegian Defence Material Agency has discussed and cooperated on the matter since then.
- Concerns about radar, radio link and intelligence systems.
- The discussion has moved from a strict evaluation towards discussing possible mitigating measures.
- NVE feel that more knowledge is needed to verify some of the statements and concerns expressed by the military.
- NVE is in favour of international cooperation regarding R&D on this subject


FFI Forsvarets forskningsinstitutt
Norwgian Defence Research Institute
Wind power consequences for electromagnetic systems
IEA
17-18/3-2005
Hans Øhra
Project manager
Principal scientist


FFI's organisation
Ministry of Defence
Defence Research Policy Board
FFI Board
Defence Research Review Board
Director General
HQ Staff
Strategy and Planning
Analysis
Information Management
Land and Air Systems
Maritime Systems
Protection

Forsvarets forskningsinstitutt

Established April 11th - 1946

- Give advice to the MoD and the Chief of Defence on the potential implications of scientific technical development.
- Advice on the best use of military technology for Norwegian defence purposes.
- Undertake development of weapons and equipment as a basis of competitive national defence industry.
- Investigate geophysical areas of importance to defence.
- Contribute to the national scientific and technical, and to industrial development.

Wind power licensing

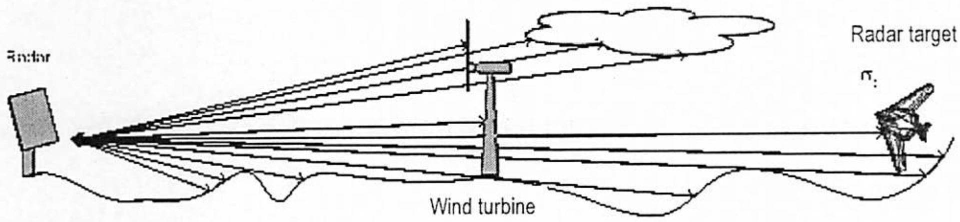
Political decisions

- Norges vassdrags- og energidirektorat (NVE) is handling and gives the licences to build windfarms
- A number of bodies is entitled to comment applications. All military interests: Norwegian Defence Construction Agency

↑

Military system interests

Preliminary study by FFI: Wind turbines potential influence on radar



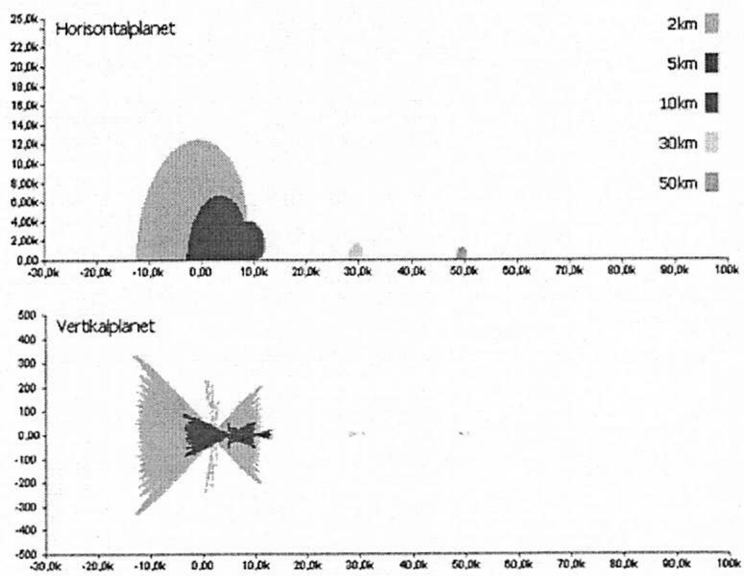
- Reflections from the wind turbine
- Reflections via the wind turbine
- Shadowing
- Radar antenna near field
- Electromagnetic noise

Erroneous target detection areas (bistatic)

Tower
h=90m
ø=3,5 -5m

Radar
E/F-bånd

Target
100m²

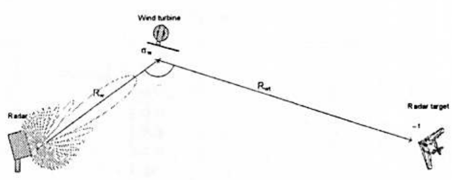


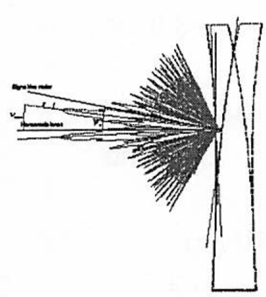
New Program - Effect of windfarms on electromagnetic systems

- MOD is the sponsor
- The purpose is to understand and reduce the conflicts and deliver at tool for analyzing conflicts
- <u>The study shall cover all aspects of radar, radio link and passive systems conflicts on 'all' frequencies</u>
- FFI does not participate in the handling of license applications

Current work

- Better RCS models of the windmill
  - Buying Spectre
  - Requesting models
- Detailed study of Norwegian radars
  - High fidelity model of radar signal processing
    - Very high stationary signal returns
    - Signal return from rotating parts
  - Field measurements?
- Effects on low frequency (<30MHz) systems
  - Direction finding
  - Signal distortion
  - Electromagnetic Noise radiation (EMI) from wind farms



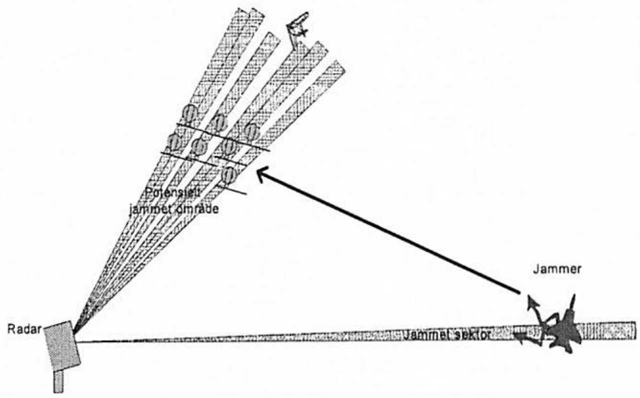


Planned work

- Develop software to support the treatment of wind farm applications – implement known expertise

- Electronic Surveillance
- VHF radar
- Radar jamming
- Radio link systems

- Mitigating measures
  - Signal processing
  - RCS reductions



Program - Effect of windfarms on electromagnetic systems

- *Collaboration and information exchange with other countries are very welcome.*

- Is it possible to establish an international group with regular meetings under IEA?

Please contact:

Hans Øhra

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Mob +47 906 76 009

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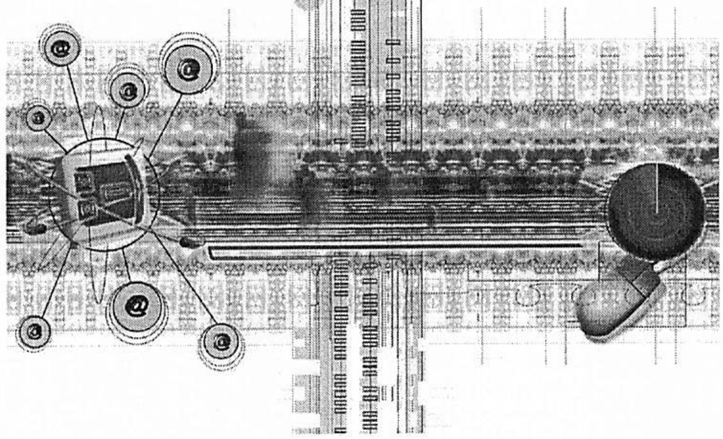
Radar and wind farm collocation



Dr Eldar Aarholt
Teleplan, Norway

IEA R&D Wind
London, March 2005

E-mail: aar@teleplan.no Tel. +47 93067077

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Contents

- Background information
- Classic problem
- Scenarios – Modern and old radar systems
- Operational considerations
- Radar system performance

Teleplan

My background

- Research scientist at the Norwegian Defence Research Establishment – Environmental Surveillance Technology Programme from 1983 to 1996
- Research areas
  - Multifrequency radar system design
  - Aircraft classification (NCTR)
  - Submarine detection (ASW)
  - Airport surveillance
- Science forums:
  Journal of Radio Science, URSI Commission F, IGARSS, CCRTS

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Present position

- Section head – Procurement
- Teleplan AS, Oslo, Norway
- Independent Consultancy Company
- Field of work
  - Large acquisitions
  - Radar and radio propagation
  - Command and control system specifications
  - Modelling and simulation

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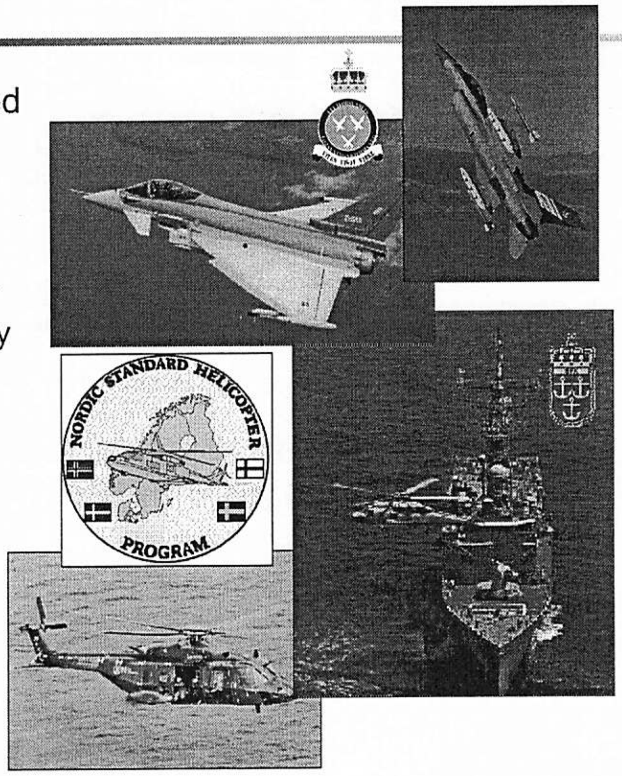
Acquisition processes

Over the past few years, I have directed the acquisition decision process of some major defence contracts exceeding €10 billion...

- New military and resque helicopters for Denmark, Sweden, Finland and Norway
- New frigates for the Nowegian Navy
- New combat aircraft for the Air Force
- New safety communication network for the national railroad
- Kuwait C4IS specification
- Qatar AOC specification
- Norwegian Public Safety Radio Project

- These have been "*smooth operations*"



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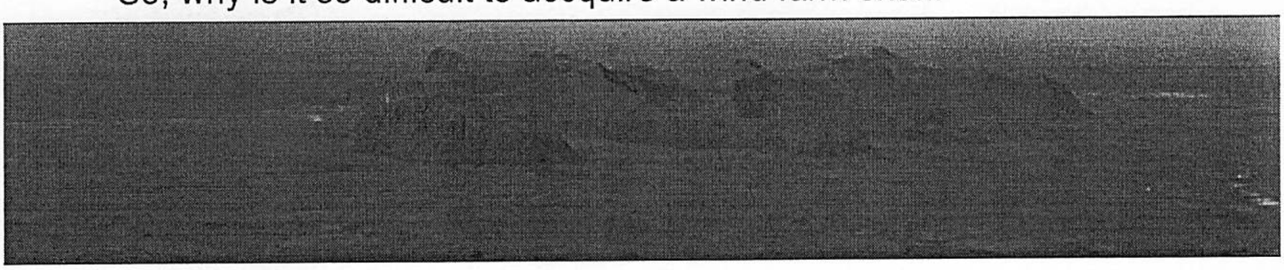
Classic problem

So, why is it so difficult to accquire a wind farm site...



- The funding is not a problem
- The investment income is good
- The local society wants it
- The tax revenues are high

- And a local military installation puts a stop to it...

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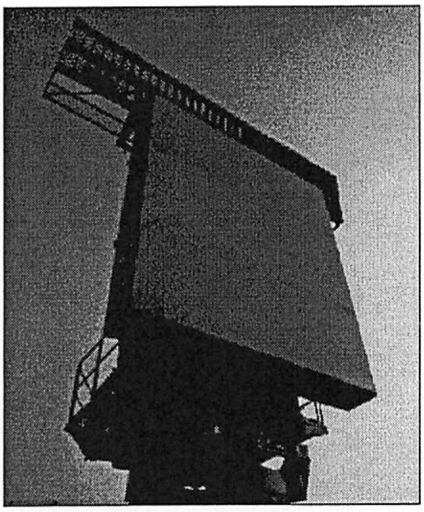
Scenario 1 – Modern radar system

- Radar installation:
  - state of the art 3D air surveillance radar
  - high performance
  - phased array antenna
  - coherent pulse doppler receiver
- Located near a planned wind farm
- License to build rejected due to military operational considerations



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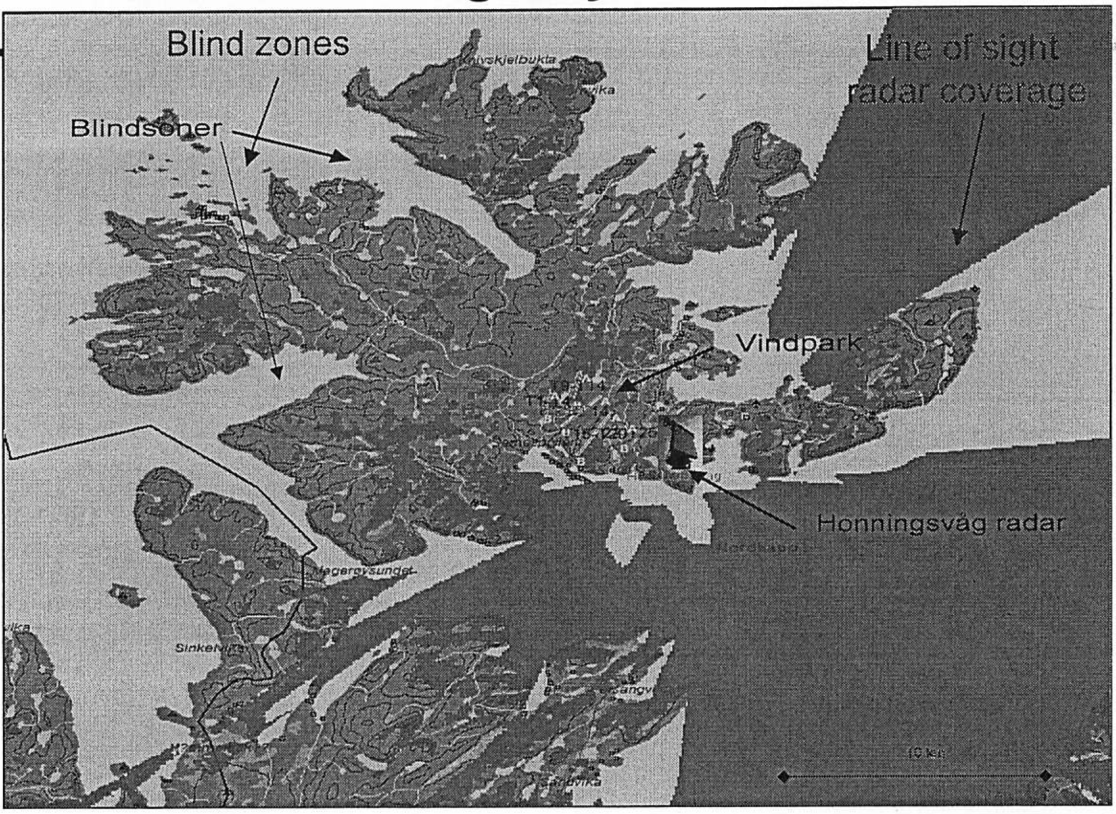
Scenario 1 – Magerøya



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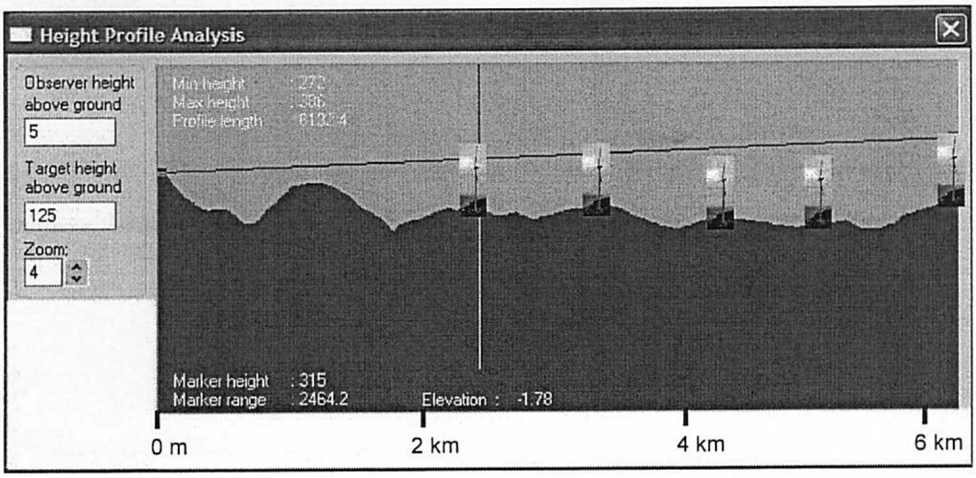
Scenario 1 – Magerøya height profile

- The highest point of the wind farm is close to horisontal elevation as seen from the radar site
- Why should an air surveillance radar look down into a mountain area?



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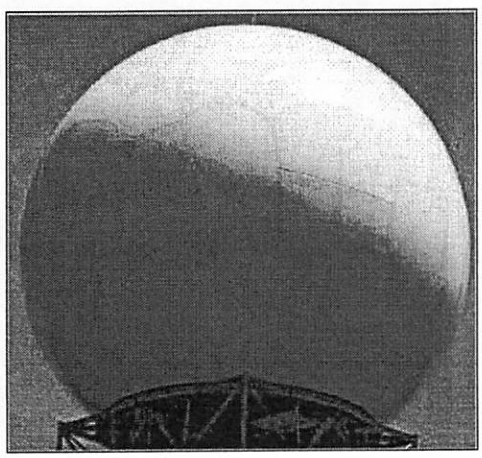
Scenario 2 – Old radar system

- Radar installation:
  - 2D air surveillance radar (airport)
  - fan antenna
  - pulse-to-pulse MTI
- Located near a planned wind farm
- License to build rejected due to military operational considerations



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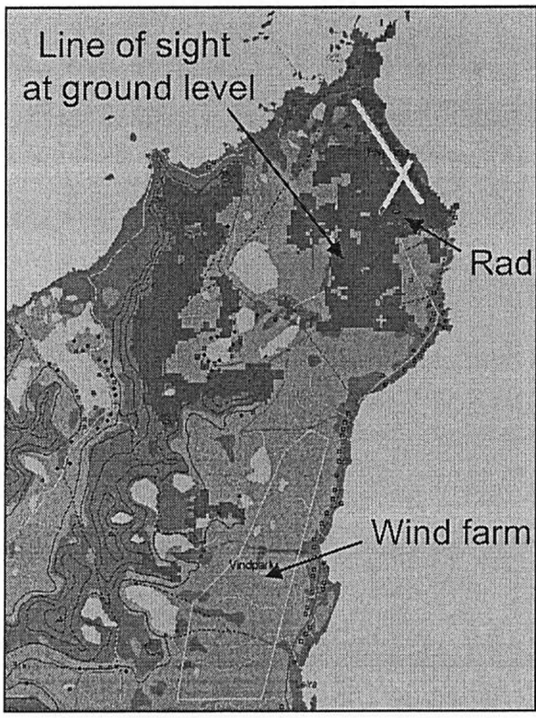
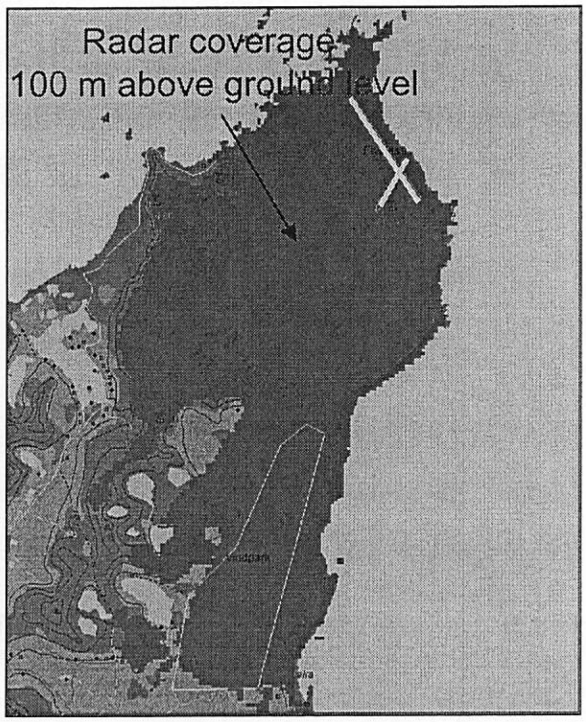
Scenario 2 – Andøya





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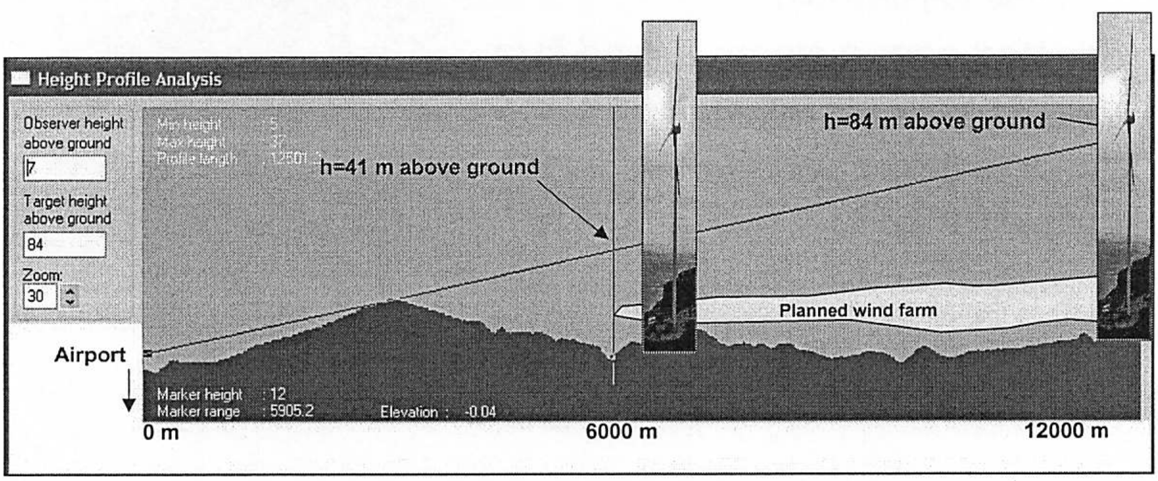
Scenario 2 – Andøya height profile

- The towers are visible from radar site
- Elevation angle +2° to +1°
- MTI will not trigger, no motion can be detected



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Operational considerations

- Operational considerations are usually left to the military; however:
- A major *annoyance* is the military doging any discussion by stating:
  - diffuse operational system requirements
  - national security considerations
  - possible intelligence installations (need to know...)
  - classified system information (but you can find it on the Internet)
  - incorrect system performance specifications (or lack of performance)
  - unacceptable system degredation without stating what is acceptable
  - excessive noise
- But in many cases:
  - Cost is the cure
- One solution is improved information exchange and dialogue

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Areas for discussion

- Why is a short distance between a radar and a wind turbine considered a problem, and what is short?
  - is 10 km separation sufficient, and if it is, why not 2 km?
  - would 100 km separation avoid the problem?
  - Is one wind turbine acceptable, two, five, ..., many?
  - Is one solution to position the wind turbine out of sight?
- A radar has no problem with distance; it works will all sorts of aspect angles, elevations and distances (although the operator must consider factors such as terrain, power and various radar target cross sections)
- What about radar signal processing, radar control and operator expertise? It is excellent, and it can get even better

Teleplan

Radar system performance

- At some point, a radar operator has to accept the existence of environmental factors; manmade or otherwise
- From a military point of view, it must be possible to agree what is considered an acceptable degraded system performance, as would be the case in a real life conflict scenario
- And in any case, it is only a matter of time before the network centric information concept makes most of the sensor systems of today superfluous

A presentation of a special windpower project in Sweden concerning coexistens between military installtions and wind turbines

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+46 70 5599833

FMV

About the studies

The studies have included following cases, investigation of:

1. Potential conflicts between radar and wind turbines
(a preliminary study and a main study)
2. Potential conflicts between radio links and wind turbines
(a preliminary study and a main study)
3. Potential conflicts between direction finding systems and wind turbines.
(a preliminary study and a main study)
4. Potential conflicts between surveillance systems under the sea level an wind turbines.
(a preliminary study)

FMV

About the project

•The project started in October 1995 by a meeting with the Swedish government.

-The reason to the meeting was that the military rejections stopped a lot of windpower projects in Sweden. In some parts of Sweden the number of rejected turbines due to military interests were very high.

FMV

What was the purpose of the studies?

1. Get an opinion of the disturbances that wind turbins cause on the Swedish armed Forces′ radar stations, radio relay links....
2. What is the meaning of these disturbances?
3. What disturbances can be tolerated without causing any major problem for the Swedish Armed forces.

FMV

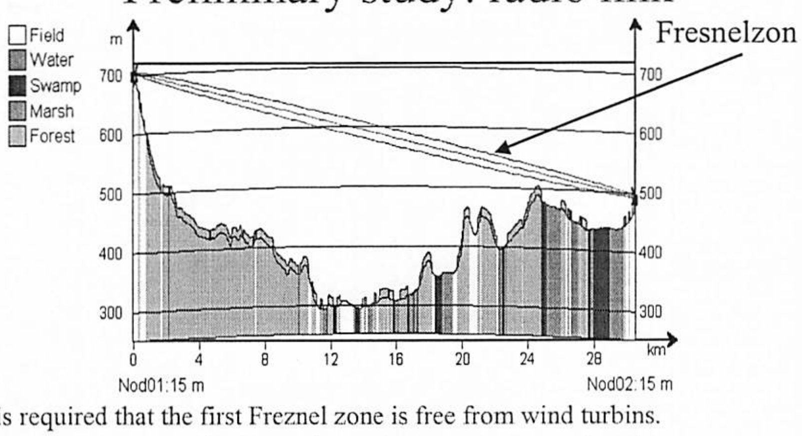
Statistics*

1993-1998	**South**	**Middle**	**North**
Number of applications	850	128	42
Military rejections:	***125***	***19***	**7**
Radar:	59	2	
Direction finding systems:	32	8	
Radio link:	20	3	
*Other reasons***:	14	6	

*1998 were about 350 turbines really established in Sweden.
-Other authorities (than the military) can have rejected the projects
-The applicant himself decides not to fulfill his/her intentions
**Rifle ranges, ammunition stores, airfields....

FMV

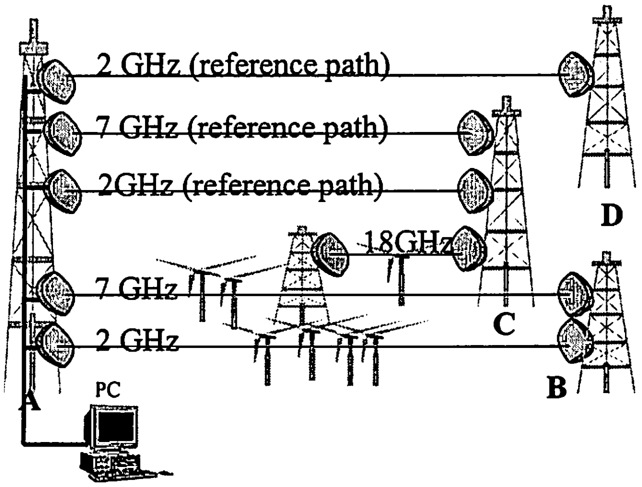
Preliminary study: radio link



•It is required that the first Freznel zone is free from wind turbins.
•For economic reason the Freznel zone is dimensioned so that the Freznel zone just touch the ground (where the distance is closest beteeen the Freznel zone and the ground).
•The Freznel zone shrinks att higher frequences.

FMV

Preliminary study: radio links



FMV

Measurements of interruption times

(SES+UAT)

2 GHz

A-B	A-C	A-D
2 h. 39 min. 52 sek	2 min. 35 sec	3 min. 3 sec

Period: aug 97-jan 99 (worst month)

2 GHz

A-B	A-C	A-D
2 h, 12 min, 31 sec	39 h, 1 sec	8 min . 27 sec

Period: year 2000 (worst month)

7 GHz

A-B	A-C
5 h, 46 min, 24 sec	30 min, 30 sec

Period: year 2000 (worst month)

FMV

Conclusions from the preliminary study: Radio relay links

•Influences from wind turbines will impair the performance of radio links in the frequency range between 2 and 10 GHz.

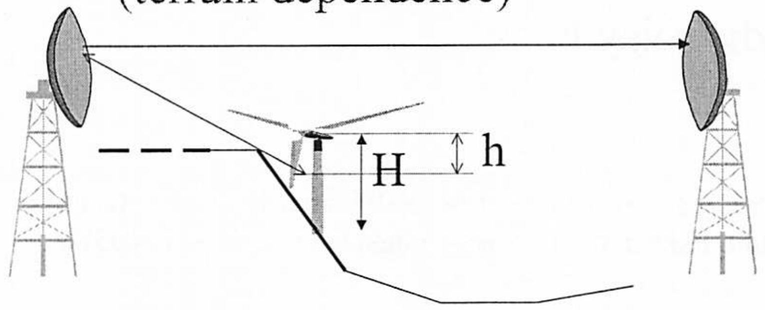
FMV

Main study: Radio relay link

•Development of a new model (earlier "free space")
 -Near field effect
 -Terrain dependence

FMV 1

Main study: Radio relay link (terrain dependence)



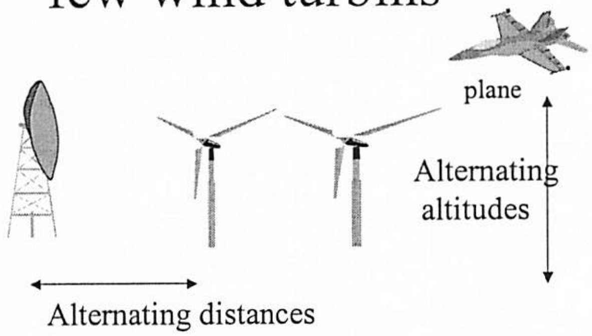
FMV

Preliminary study: Radar

1. Performance measurements on radar under influence from just a few wind turbines (two).
2. Performance measurements on radar under influence from several wind turbines. (about 50)

FMV

Measurement situation 1: few wind turbins



Measurement situation number two is almost equal. Just more turbines.

FMV 1

Preliminary study radar: conclusions

1. Few turbins:
   -No negative effects at all.

2. Several wind turbins:
   -No problems were discovered about the probability of detection. The tracking will have some problems when the plane is "over and within" the area of turbins.

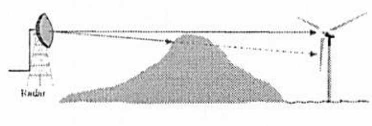
FMV 1

Main study: radar

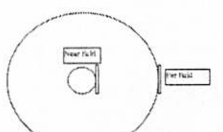
- Measurements of the radar cross section area
- Theoretical and experimental study of the terrain influence
- Development of models.

FMV 1

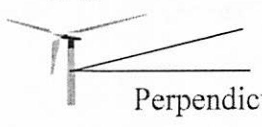
Main study radar: conclusions



Terrain dependence
"blocking"



Near field effect



Perpendicular incidence ("Worst case")

FMV 1

Surveillance systems under the sea level (a limited preliminary study)

- Measurements have been made in the Baltic sea
- The measurements included five off shore turbins.
- The surveillance systems are "quit systems" or passive systems. They are just "listen" to different kind of signals. They don't generate any signals themselves.
- Three aspects have been studied (measurements on different distances).
  - -hydroacoustic
  - -electromagnetics (electric- and magnetic fields).

FMV 1

Some (conclusions) and comments

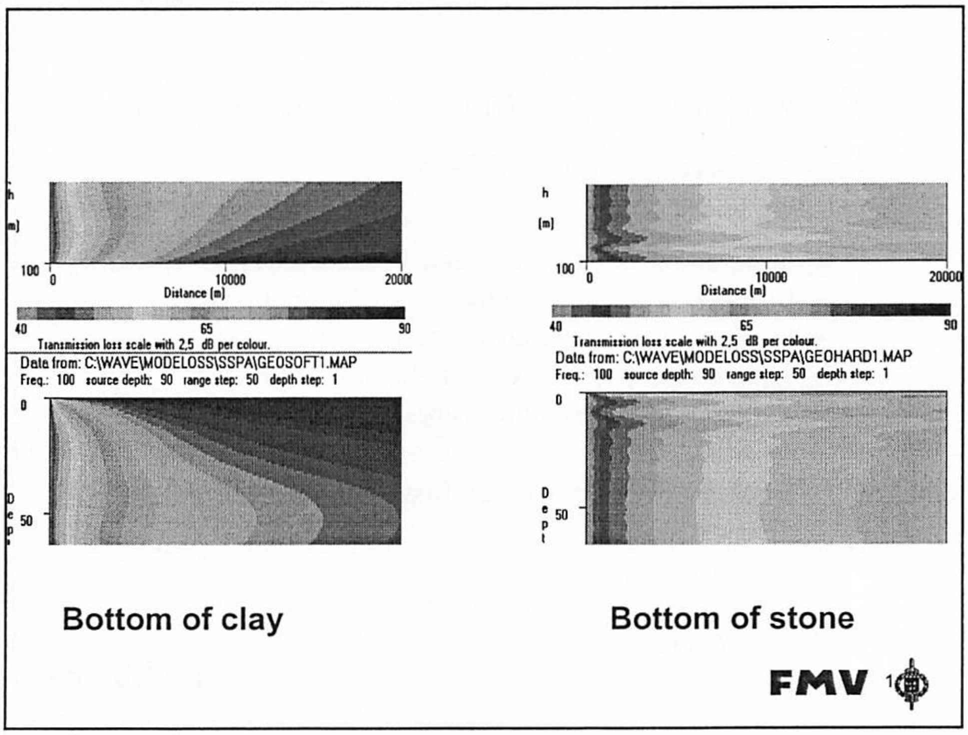
Hydroacoustics:

- The results are associated with the special conditions on the chosen place, so they are not so interesting.
- A deeper study about the wind-forces is needed.
- The water condition (shallow water, deep water)
- The sea bottom? Stone, clay?
- The turbins construction and size?

Elctromagnetics

- It is the alternating current (AC) that causes disturbances, not the direct current(DC).
- To complete the measurements.

FMV 1



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Bottom of clay
Bottom of stone
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FRA

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APPENDIX 1

IEA R&D
Expert Meeting on Radar, Radio Links and Wind Turbines.
London, 17 – 18 March 2005

Your reference	Your date	Your file code
Mr. Kjell-Åke Eriksson, FMV	2002-09-25	24682 – LB604444
Our reference	Our previous date	Our previous file code
Mr. Bo Lithner		

EFFECTS FROM WINDMILLS ON COMMUNICATION AND ELECTRONIC INTELLIGENCE SYSTEMS

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1. EXECUTIVE SUMMARY

1.1 Objectives of the study

The Swedish National Defence Radio Establishment (FRA) was as experts in the subject field contacted 1998 – 1999 and 2002-2003 by The Swedish Defence Materiel Administration (FMV) to investigate effects on signal intelligence (SIGINT) systems from large-scale offshore windfarms.

SIGINT is one of the main technical reasons, in addition to radar, why offshore windfarms are rejected by the government in the building application process. The purpose of this study was to define new criteria's for approval of building permit and the possibility of technical modifications of SIGINT systems to minimize interference from windmills.

1.2 Background to problems created by windmills

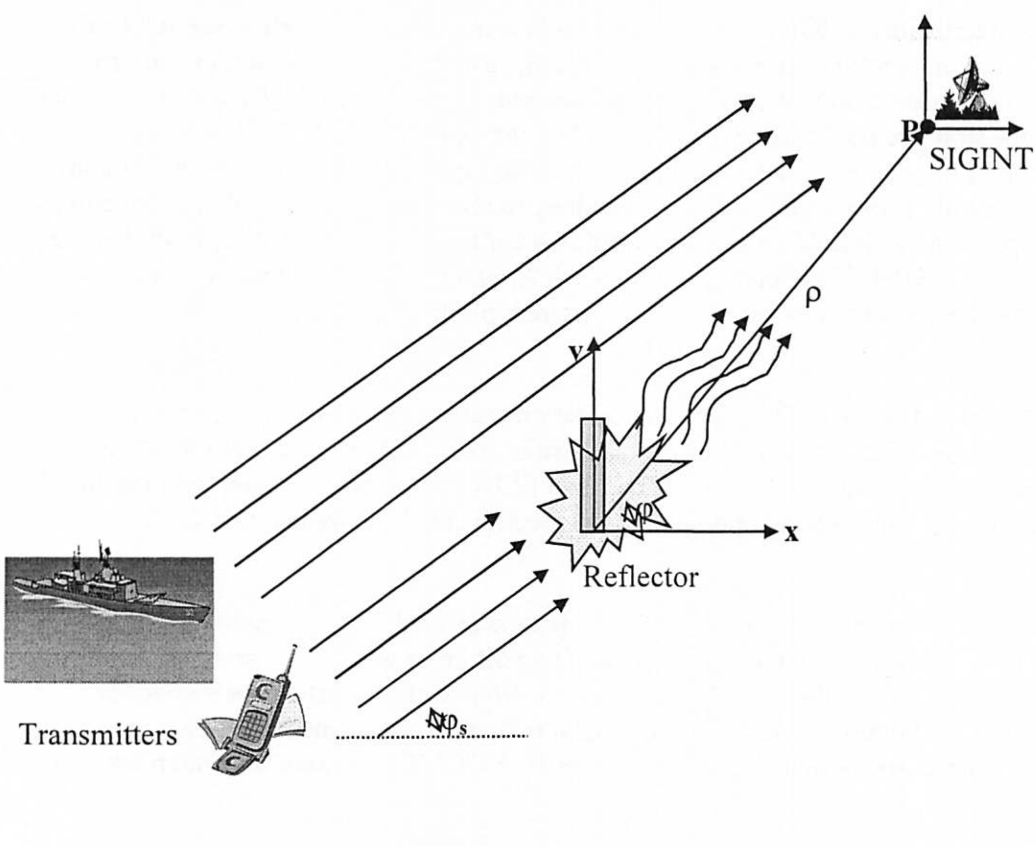
Signal intelligence (SIGINT) can be divided in communication intelligence (COMINT) and electronic intelligence (ELINT) targeted against tele- and datacommunications respectively non-communication systems, i.e. radar systems. SIGINT collection is done both for strategic intelligence purposes and on the tactical level for location and identification of targets. For SIGINT collection the National Defence Radio Establishment (FRA) mainly uses a chain of fixed sites along the Swedish coast line, which are complemented with a SIGINT ship (Orion) and two Gulfstream IV (S102B) aircraft. On the tactical level SIGINT is done by the Swedish Armed Forces using Special Forces or Electronic Support Measures (ESM) on different platforms.

SIGINT of today is not aimed only at military targets but also to a high degree at civilian targets. Therefore are civilian authorities like the Swedish Coast Guard also depending on the capability of COMINT and ELINT systems, for example in rescue operations and for tracking and identifying specific ships in Swedish waters.

What is the problem with windmills? Multipath is created when the radio signal from an emitter (transmitter) to the receiver is travelling different ways. This problem occurs when the radiowave, due to reflection, is scattered because of natural or man made objects like windmills. The amount of signal reflection can be mathematically described by the radar cross section (RCS) of a windmill. A COMINT station may intercept both the direct and the reflected signal from the emitter at the same time which makes it difficult to perform direction finding (DF), see figure 1. In figure 1 a part of the electromagnetic field, the wavefront with the incidence angle φ_s, is scattered in the reflector, a windmill tower, and is received in location $P = F(\rho,\varphi)$ simultaneously with the direct signal. Normally detection and demodulation, i.e. capturing signal message content, is not a problem because of the large difference in signal levels.

ELINT with great system sensitivity, due to high gain antennas, measures both main- and sidelobes of radars in the scenario, mainly from ships or aircraft. ELINT is also capable of measuring reflections of radar mainlobe in windmills, i.e. like bistatic radars. Reflections from radar sidelobes are normally below system sensitivity. Tactical ESM systems have less sensitivity and therefore can't detect reflections from the radar mainlobe if not located nearby the windfarm. Reflected signals intercepted by ELINT/ESM can be interpreted as real emitters and therefore reported to the command and control system. Reflected signals are often distorted and correct identification is not always possible, generating unknown or false identities, and can also depending on system design during unfortunable conditions hide real emitters in the windmill direction.

Figure 1: Multipath



1.3 Study of windmills and ELINT

ELINT is, in addition to direct signals from emitters, also detecting radar mainlobe reflections from windmills when the receiving antenna is pointed in their direction. Simply filtering out reflections could easily degrade the ELINT systems ability to intercept other real weak signals in the direction of windmills. Therefore automatic ELINT system, i.e. high sensitivity ESM capable of data collection, must be capable of measuring and handling reflections without capacity degradation.

This study, carried out 2002-2003, has focused on investigating the characteristics of reflections, effects created by automatic signal processing and methods to identify emitters created by reflections and logically mark (block) them in the active emitter file (AEF) of the ESM system. The ESM system investigated, modified and tested in the study was AutoTES, with SaabTech AB signal processor PPY. AutoTES is part of the Swedish Army Signal Intelligence Battalion (SISBAT).

The ability to handle reflections in existing automatic ELINT/ESM systems on the market was prior to this study limited to navy operations in Littoral Warfare regarding reflections from nearby ships, cliffs and objects on islands. Principles for interference cancellation from nearby objects, 10 – 1000 meter, were not able to handle multiple reflections from windfarms at long distances, i.e. miles.

This study has accomplished development of algorithm modifications in the signal processor from SaabTech AB resulting in a verified and validated system capable of handling reflections from windfarms. The work carried out together with SaabTech AB has been very constructive, well documented, within delivery time and the result was new software delivered to the Swedish Army.

Study results showed that:

- reflections are mostly marked as Multipath.
- correlation is done to real emitters if the reflected signal has equivalent signal parameters.
- modifications have no negative effect on contracted technical/tactical scenario used for system delivery approval.

Observed remaining problems:

- 5 – 10 % of reflections are still propagating through the system. This small amount can be tolerated and handled by the ELINT operator.
- the modified signal processing can hide identical emitters behind the windfarm. This can only be handled by cooperating systems with coverage of the area, i.e. triangulation between two deployed systems.

Suggestions for further algorithm improvements of the system also exist, i.e. reducing the 5 – 10 % above, but they are not considered as necessary. Every type of signal processor is contractor specific but equivalent modifications should be possible in other systems. The cost of modification can roughly be estimated to 5 – 10 MSEK per type of processor, our study cost was about 5 MSEK. Ability to handle reflections is now a recommended requirement in future acquisitions for use by the Swedish Armed Forces.

For more detailed information regarding ELINT and windmills see chapter 2.

1.4 Study of windmills and COMINT

COMINT direction finding (DF) is, in the receiving point of location, affected by the distorted phase of the wavefront created by multipath propagation. As part of this study The Swedish Defence Research Agency (FOI) 1998-1999 calculated radar cross sections (RCS) using FEMAP (CAD software) and FEKO (electromagnetic solver) for 25, 50 and 80 meter windmills at HF (2 – 30 MHz) and VHF (30 – 300 MHz). RCS above 1 GHz has been investigated and reported earlier by FOI.

FOI also developed a statistical model for DF errors from groups of windmills at different locations. Calculation from a group of nineteen 80 meter windmills showed a DF error mean of about 1.9° rms (integrated $\pm$ 90°) with protection range of 10 km and target at 5 km from the windmills. The result clearly indicated that earlier, since 1988, used fixed protection ranges 10 km and 50 km for HF respectively VHF/UHF was to strict.

The FOI study has resulted in executable software for estimation of DF errors using the commercial products FEMAP, FEKO and MATLAB. Since no contract yet has been issued from the Swedish Armed Forces to buy this software FRA decided to create a simplified model implemented in MS Excel based on the findings. When using the new model DF error can be handled regardless of frequency. The simplified model was also adapted to compensate for change of windmill tower height and modern digital beamforming. With this model windmills can be tolerated if the calculated total DF error is less or equal to the DF system instrumented error. This simplified model is now in use in the building approval process.

For more detailed information regarding COMINT and windmills see chapter 3 and appendix 1.

1.5 Conclusions and recommendations

Before this study the demand for protection ranges, defined during the 80's, was deeply questioned by the windpower industry. This study has confirmed existing problems, increased our knowledge and created a common understanding within the windpower industry and building commissioners.

Computer simulations of today provide better means of interference calculations and digital signal processing has improved the modern SIGINT equipment. Therefore new models for approval of windfarm building permit for ELINT and COMINT were created as a result of this study and they are now in use by FRA.

The study also resulted in verified and validated signal processing modifications allowing SISBAT AutoTES to cope with reflections. For automatic ELINT/ESM the protection range is reduced from 100 km to 10 km when using "reflection hardened" systems. Along the cost line this means that the protected area is reduced from about 200x100 km to 20x10 km for an automatic ELINT site location.

Regarding manual ELINT collection the study has showed that real signals in direction of windmills can be hard to separate from reflections. This is especially true for the operator in real time and also hard during off-line analysis of digital registrations. Occurrence of reflections in the frequency spectrum also tends to trigger unwanted interception i.e. locking the system and reducing available time for detection of real signals. With lots of signals in a frequency band the situation is severe. A consequence of problems mentioned above is that weak signals can be undetected considering the interference from reflections. The recommendation from the study is therefore to keep the 100 km protection range in the main reconnaissance sector for the fixed ELINT sites where manual collection take place. In other directions ESM can provide tactical coverage and tip-off to the manual ELINT operator, i.e. with the reduced protection range of 10 km.

Reflection hardened ESM technology will, dependent on time of new investments, be used in all (fixed and remotely controlled) ELINT stations along the Swedish coast line to reduce the required protected areas. In cases where offshore windfarms are going to interfere with ELINT sites building commissioners are offered paying for the damages, i.e. for investment in the required ELINT equipment. Considering the project cost of often many billion SEK this would be a small fee for the permit.

2. ELECTRONIC INTELLIGENCE SYSTEMS

2.1 Bistatic radar equation and signal detection

Bistatic/multistatic radar is a technology with many applications in the future defence structure. A bistatic radar has, compared with a monostatic radar, different locations for transmitter and receiver. The basic principles of bistatic radar can also be applied to ELINT/ESM detection of reflections in windmills from radars illuminations. However some environmental differences exists. Radarsystems for air survecillance must be able to detect small targets with radar cross sections (RCS) about 0.1 – 10 m^2. Windmills presents a typical RCS of 1000 - 10000 m^2. Microwave radars uses line of site detection but ELINT also uses ducting and troposphere scatter for long distances detection, especially over sea.

Using the radar equation shows that signal detection is possible if P_s, $P_j \geq S$

$$S = k * T * B * NF * SNR * 4 * \pi / (\lambda^2 * G_m * G_p)$$
$$P_j = P * G_s * \sigma / ((4 * \pi)^2 * \beta^2 * \rho^2)$$
$$P_s = P * G_s / (4 * \pi * \alpha^a)$$

k = Boltzmann constant = $13.8 * 10^{-24}$ [J/K]
T = temperature, about 290 K
B = bandwidth
NF = system noise factor
SNR = signal to noise ratio
G_s = transmitter antenna gain
G_m = receiver antenna gain = $4 * \pi * A_m / \lambda^2$
G_p= process gain
A_m = receiver antenna aperture
λ = wavelength
σ = radar cross section (RCS)
P = emitted power
P_s = power of direct signal
P_j = power of reflected signal
S = system sensitivity threshold
α = distance between emitter and receiver
β = distance between emitter and reflector
ρ = distance between reflector and receiver

Let us do some calculations to see if ELINT systems have the ability to detect reflected radar signals. Technical data used in this generic example below:

Radio Frequency	: 9400 MHz (navigation radar)
Effective Radiated Power	: 100 dBm
Distance to emitter	: 25 km
RCS	: 1000 m^2, (stealth adapted tower)
Antenna height	: 15 – 37 m, radar horizon 25 km, at target < 5 m
Antenna gain	: 35 dB
Sensitivity	: at SNR 15 dB and NF 11 dB:
	- 56 dBm bandwidth 2000 MHz
	- 61 dBm bandwidth 500 MHz
	- 75 dBm bandwidth 20 MHz
	- 81 dBm bandwidth 5 MHz

Table 1: Received signal levels

Range =>	5 km	10 km	15 km	20 km	25 km
Direct - Radar mainlobe					- 4 dBm
Direct - Radar sidelobe					- 44 dBm
Reflected – Radar mainlobe	-57 dBm	-61 dBm	-61 dBm	-57 dBm	
Reflected – Radar sidelobe	-97 dBm	-101 dBm	- 101 dBm	-97 dBm	

With receiver antenna gain 35 dB the reflected radar mainlobe – 61 dBm can be detected with a receiver bandwidth of 500 MHz or less. Direct signals (range 25 km) from radar mainlobe and sidelobes are 57 dB and 17 dB over this level and can therefore easily be separated from reflections. For an interferometer or amplitude monopulse system with 0 dB antenna gain the level of reflected mainlobe is - 96 dBm and the system therefore can't detect reflections. A more typical RCS, 10000 m^2, will produce 10 dB higher signal levels but not enough to detect reflections with a 0 dB system. It can also be shown that the best location for windmills always is in the middle between the emitter and receiving system.Windmills at a closer range to the emitter or the receiver are equivalent bad.

Modern ESM equipment often has noise floor estimation and floating detection threshold, equivalent of Constant False Alarm Rate (CFAR) processing in radar systems. One early concern was that windmills could raise the background signal level. Measurement done during this study has not shown this effect but with other system design and high signal densities a potential problem could occur. A quick fix would then be to prohibit noise measurements in direction of the windmills.

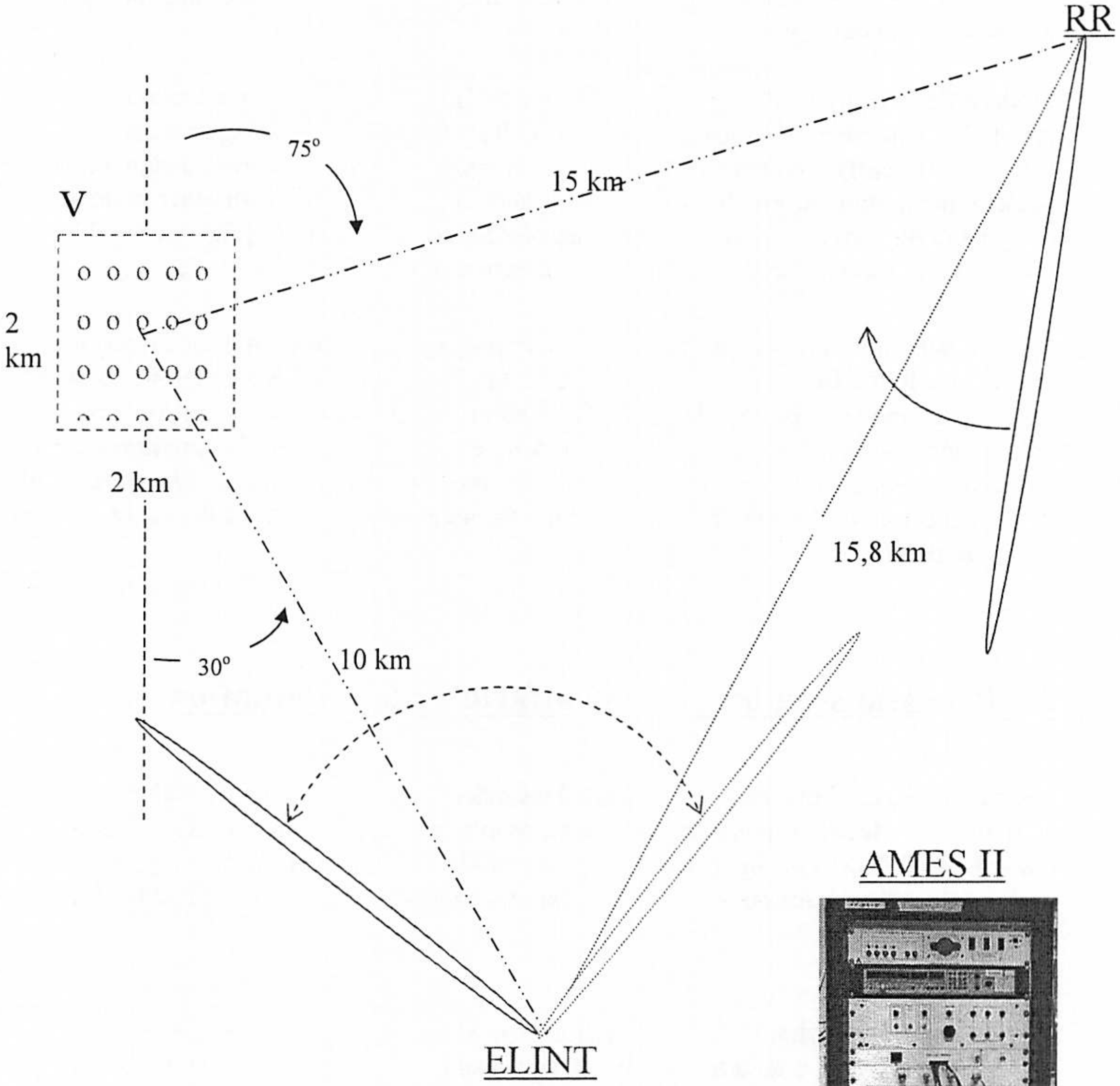
Beyond radar horizon ducting, due to anomaly propagation, is required for detection of reflections. In the Baltic Sea there are excellent to fair conditions more than 63 % of the time. Receiving signals from distances far beyond 100 km, i.e. used protection range, are not unusual. When located in a duct the whole tower of a windmill sometimes does not reflect the signal, i.e. RCS is less. Of course the windmill also has a radar horizon of its own and we don't know from time to time the actual RCS. We have therefore chosen to ignore this fact.

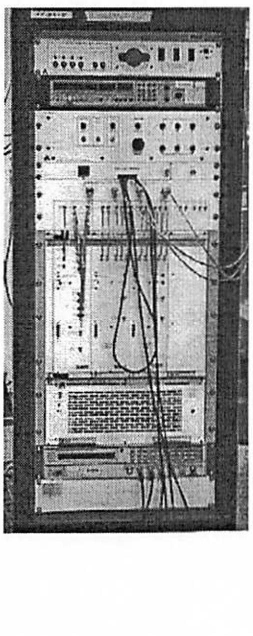
2.2 Problem scenario and windfarm radar simulation

The initial phase of the study concentrated the effort on understanding signal characteristics of reflections in windmills and the problems caused in the unmodified automatic ELINT/ESM system. This was done by Matlab simulations, study of system design (algorithms), executing radar simulations with Northrop Grumman Ames II and ESM field testing.

For windfarm radar simulation a test scenario presented in figure 2 was used consisting of 25 windmills (V), one radar emitter (RR) and an ELINT system with sector scanning antenna. RR with circular scan successively illuminates the ELINT system and the windfarm. If the ELINT antenna is directed towards V then reflections are measured.

Figure 2: Windfram test scenario.





The radar emitter (RR) can be given different radar modes to stimulate different problems in the automatic signal processing. The modes used are defined below:

Mode 1 (Navigation radar ~ short pulse)

Scan : circular
RF : 5900 MHz
Pulse width : 0.2 μs
PRI : 250 μs

Mode 2 (Surveillance radar ~ medium pulse width with PMOP)

Scan : circular
RF : 5900 MHz
Pulse width : 3 μs, biphase coding with sub-pulse width 0.2 μs
PRI : 330 μs

Mode 3 (Surveillance radar ~ medium pulse width with FMOP)

Scan : circular
RF : 5900 MHz
Pulse width : 3 μs, linear frequency modulation on 5 MHz
PRI : 150 μs

Mode 4 (Surveillance radar ~ long unmodulated pulse)

Scen : circular
RF : 5900 MHz
Pulse width : 18 μs
PRI : 300 μs

Radar mode 1 is expected, due to the short pulse and distance between windmills, to create bursts with mainly separated pulses. During radar mode 2 and 3 the pulse will overlap between windmills and effects of phase shifts in combination with the pulse modulation PMOP or FMOP can be investigated. Using mode 4 the phase shifts could be investigated independent of pulse modulation and this pulse was also expected to create greater pulse width. During the study three main characteristics of reflections could be found:

Case 1: An identical signal is created by reflection in individual windmills by a narrow antenna mainlobe.

Case 2: A burst of pulses is created by successive or/and parallel reflections in different windmills. False PRI values are created. Depending on the radar antenna pattern illumination of windmills reflections can have different amplitude.

Case 3: Pulse overlap is created. Like in a jω-diagram a resultant R_{n+1} is created by vector addition of pulse P_n and pulse P_{n+1}, and so forth. Depending on different time of propagation the resulting pulse gets arbitrary amplitude and phase.

Simulations, with the scenario described above, generated depending on radar mode 1-4 between 2-8 false emitters in the ESM system active emitter file (AEF). AEF signal parameters created for these emitters did not at all resemble the real emitter illuminating windmills, with exception of one created emitter. The main signal parameters investigated where:

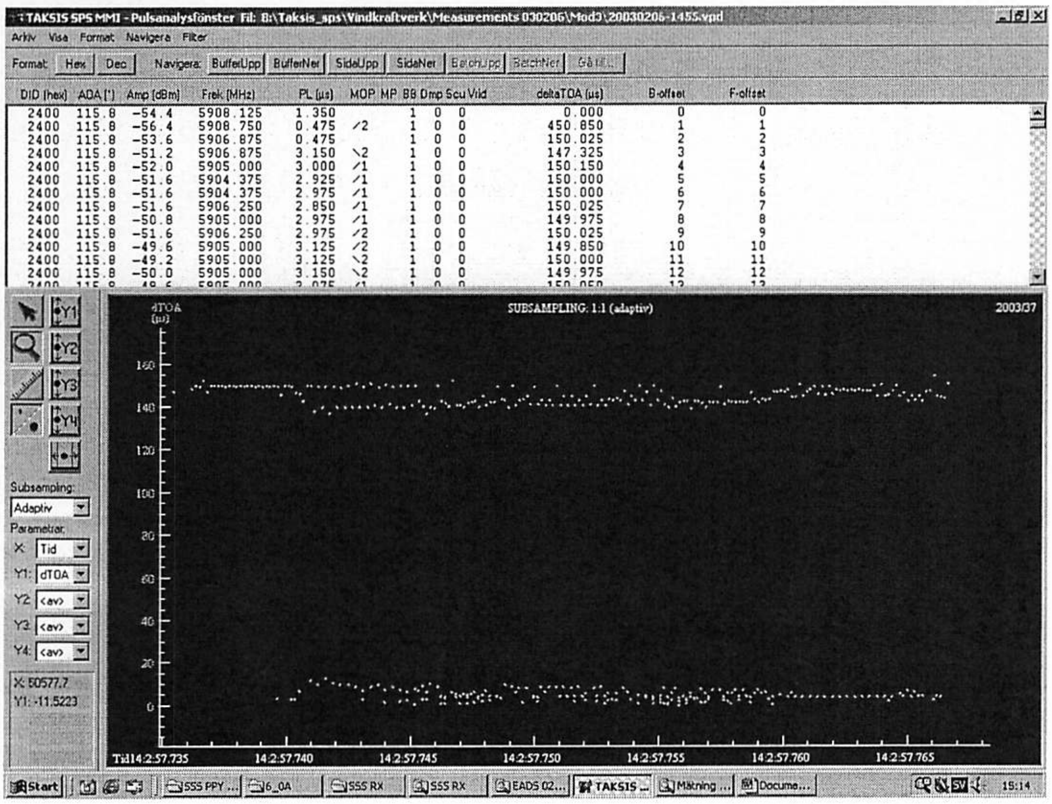
- Amplitude
- Radio Frequency
- Pulse width
- Delta Time of Arrival (dTOA) = Pulse Repetition Interval (PRI)

Amplitude measurements, see also figure 9, show how the antenna sweeps over the windfarm. Depending on where on the antenna diagram different windmills are hit several parallel reflections with different amplitude occur.

Regarding RF the technique for RF measurement is Digital Instantaneous Frequency Measurement (DIFM). An initial concern was that DIFM could be affected by pulse overlap, i.e. simultaneous signals with different phase, but the study did not show great distribution of RF measurements. The reason for this is that RF for the test object is measured at the front of the pulse and pulse overlap occurs in the back of the pulse. RF was due to that fact the most stable signal parameter.

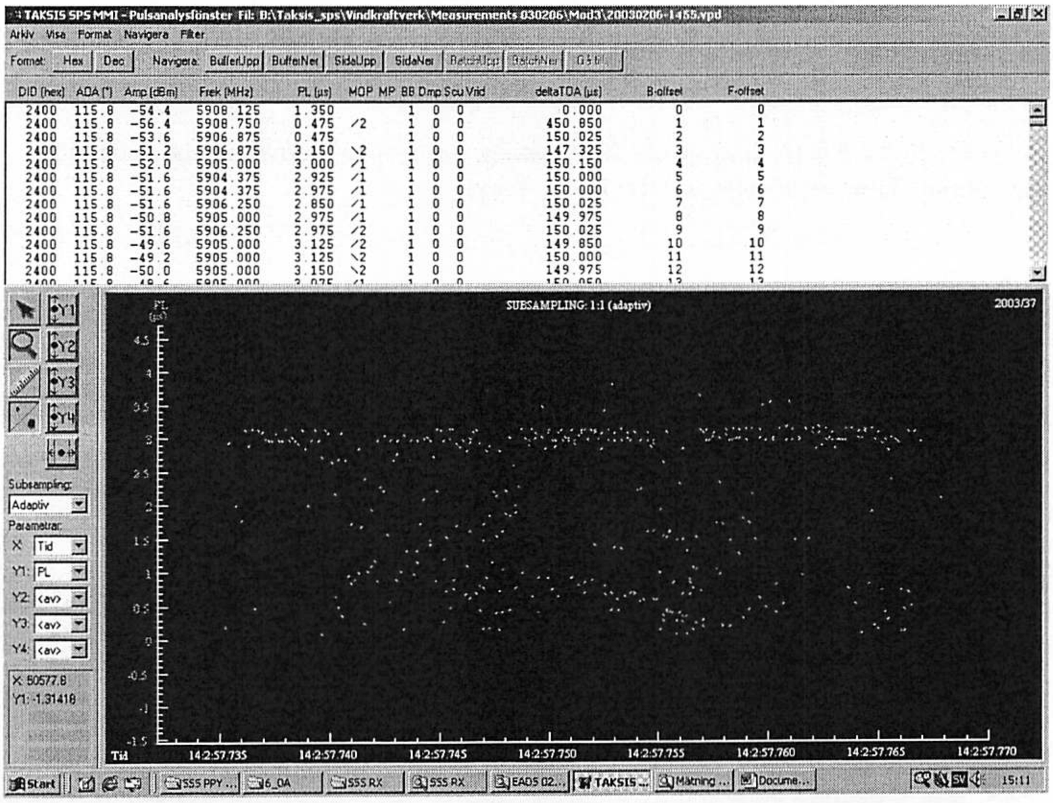
Delta Time of Arrival (dTOA), also designated Pulse Repetition Interval (PRI), distribution is shown in figure 3. Correct dTOA measurements create a straight line at the top of the diagram (about 150µs). A large number of synthetic dTOA are also presented in the lower part of the picture, the line above 0µs. Synthetic dTOA is generated by many reasons like multiple reflections (case 2 above), reflections of reflections and signal processing problems. Typical indication of dTOA distribution is the best (primary) indicator for identification of emitters generated by reflections.

Figur 3: Mode 3 – dTOA during one illumination. True signal at the top and reflection at the bottom. Time on X-axis and dTOA on Y-axis.



Pulse width, see figure 4, is varying during an illumination. In the figure some correct pulse widths (3μs) are showed at the top of the diagram. Otherwise false pulse widths are created due to the fact that overlapping pulses create phase shift and amplitude dipping indicating end of pulse measurement. We could not indicate any lengthened pulses that may occur with another system design. Indication of random pulse width distribution can be regarded as the second best indicator for finding of emitters generated by reflections.

Figure 4: Mode 3 – pulse width measurement during illumination of three windmills.



To confirm the results of windfarm radar simulations the ESM system was also field tested at the wind farm Näsudden at Gotland, see description of the activity in section 2.4.1. The test in real signal environment unambiguously showed the same results as testing of the ESM system with AMES II radar simulator.

During and after system modifications several simulations and field testing also were performed for verification and validation (V&V) of changes. A more advanced scenario simulating emitters in field test 2 section 2.4.2 was also used for V&V. Before the final field test 2 with the modified ESM system acceptance test with radar simulator showed that new system functions for handling reflections were satisfactory and robust. A complementary test with a large scenario with many different types of emitters, used for tactical/technical ESM system acceptance test, was also executed showing unchanged or in some cases improved capability.

2.3 System modification

FRA has on contract from the Swedish Armed Forces developed and produced the Swedish Army Signal Intelligence Battalion (SISBAT), consisting of three companies with COMINT-, manual ELINT and automatic ELINT/ESM system. The automatic system, was the test object in this study. It is called AutoTES and consists of antenna and receiver system produced by FRA and Signal Processing System (SPS) produced by SaabTech AB. SPS performs signal digitalization (Measurement Unit), signal processing (Correlator PPY), data communication (EW- computer) and on Operator Console identification, presentation, control, analysis and registration.

Section 2.2 described the initial phase of this study where the problems with windmills and signal characteristics where investigated. For the three found problems, cases 1) identical signal, 2) burst of pulses and 3) pulse overlap, we had to take actions in the SPS signal processing. It was early established that changes could be limited to software, since SPS is based on a combination of Field Programmable Gate Array (FPGA) and Digital Signal Processors (DSP). Beside these modifications we also did some changes to operator presentation regarding multipath on the MS Windows based Operator Console. The main changes are presented below.

Improved glitch handling

Pulse overlap with phase shift and amplitude dipping causing termination of pulse measurement were addressed in Measurement Unit by more intelligent "glitch" handling, i.e. considering glitch characteristics and time delays.

Identification and multipath marking

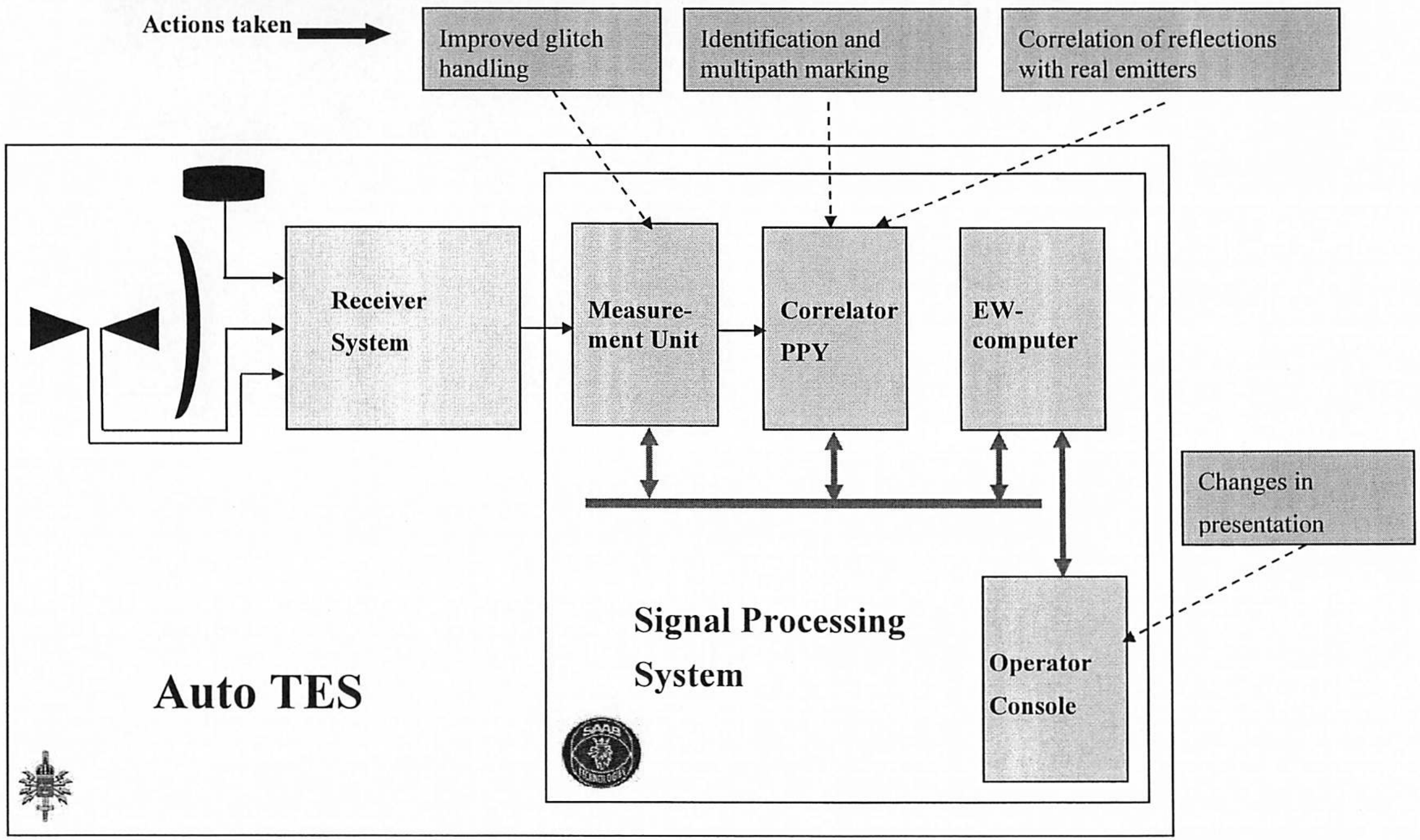
Histograms with dTOA from emitter bursts of pulses were analysed for the characteristics of reflections, i.e. synthetic dTOA(PRI) near 0μs. Emitters fulfilling indications of reflections will be marked "Multipath", requiring operator decision before being externally reported. As an optional complement, not implemented by the study, the same technique probably could be applied to pulse width.

Correlation of reflection with real emitters

Reflected signals identical to real emitters in the scenario are handled by trying to correlate all emitters not marked "Multipath" in the known sector(s) with windmills to all other AEF emitters. If correlation criteria's are fulfilled the reflected emitter is marked with a reference link to the real emitter and thereafter suppressed, i.e.not externally reported. This principle can in exceptional cases hide real emitters behind the windmills. Based on triangulation with another ESM system the operator in such cases can break the reference link and start reporting of the emitter.

In ESM systems signal processing is done by either de-interleaving or correlation, the latter is used by SaabTech AB. Based on our experience the same principles of modifications suggested in this document can be applied to both principles. Of course implementation will change and since every implementation is contractor specific new unforeseen problems may exist. Therefore a similar modification program is required for each type of product and/or contractor. The cost of modification can roughly be estimated to 5 – 10 MSEK per type of signal processor. Our study cost was about 5 MSEK.

Figure 5: The modified automatic ELINT System



2.4 Field tests on Gotland

2.4.1 Field tests with unmodified system

A field test with the unmodified ESM system was accomplished early in the project at Bockstigen and Näsudden windfarms on the island of Gotland. The Signal Processing System, see section 2.3, was temporary installed in a mobile ELINT unit, including receivers, see figure 6. As a target ship illuminating the windmills we, due to bad weather conditions, used the rescue cruiser Amalia Wallenberg from The Swedish Sea Rescue Society with navigation radar.

Figure 6: Mobile ELINT at Näsudden during field tests.

For target tracks we used similar but not identical tracks presented in figure 11. The ESM system performed as expected from earlier radar simulations. Figure 7 shows the result from delta Time of Arrival (dTOA) measurements at Bockstigen with five offshore windmills. The picture presents real dTOA at the top and reflections at the bottom. Figure 8 also shows expansion of first and second order of reflections. The bending of first order reflections is created by geometrical changes as the ship follows the target track. The measurement on the windfarm Näsudden is presented in figure 9. At the left we can see the amplitude top of the direct signal and after a time delay the amplitude distribution of the wind farm, at the right. As we also can see in the picture we only measure false dTOA (PRI) during the illumination of the wind farm.

Figure 7: Bockstigen track 3 - True signal at the top and reflection at the bottom. Time on X-axis and dTOA on Y-axis.

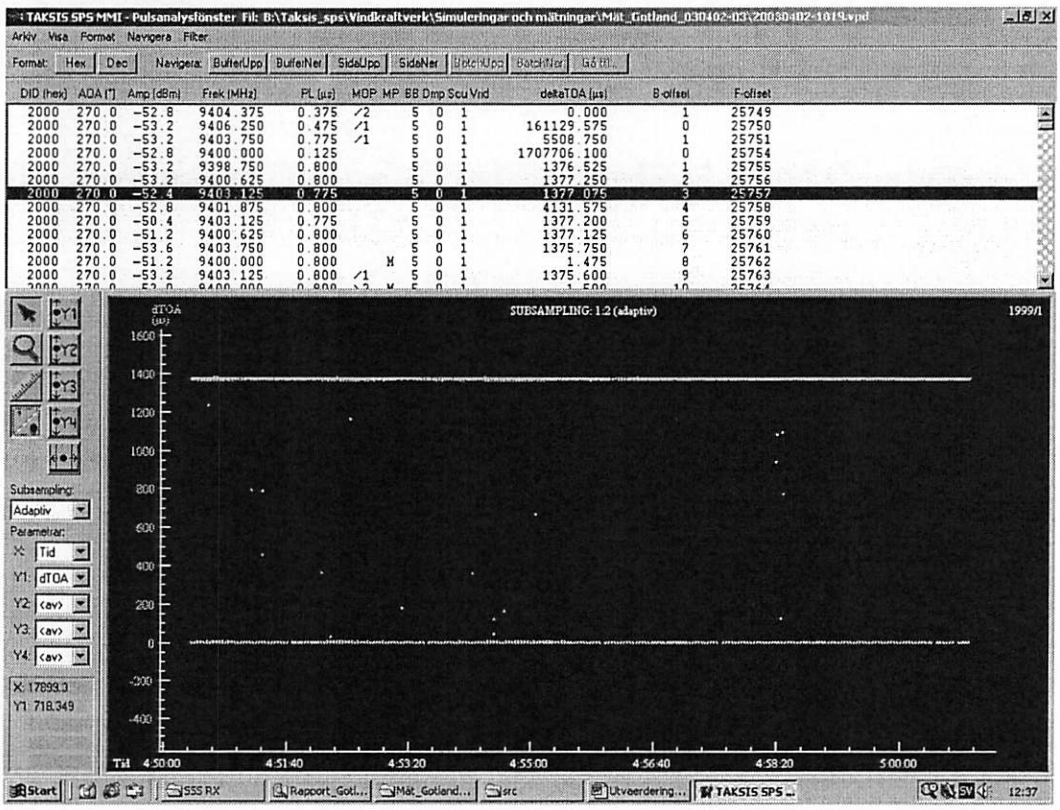


Figure 8: Bockstigen track 3 – Expansion of figure 7 reflections.

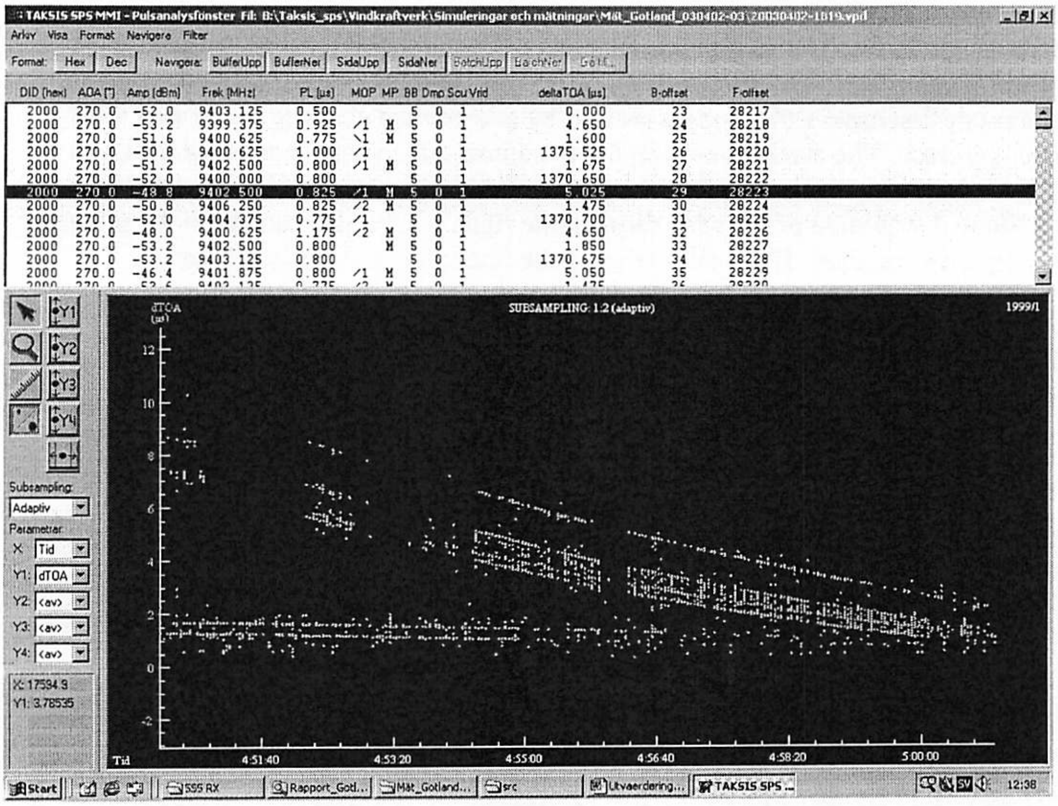
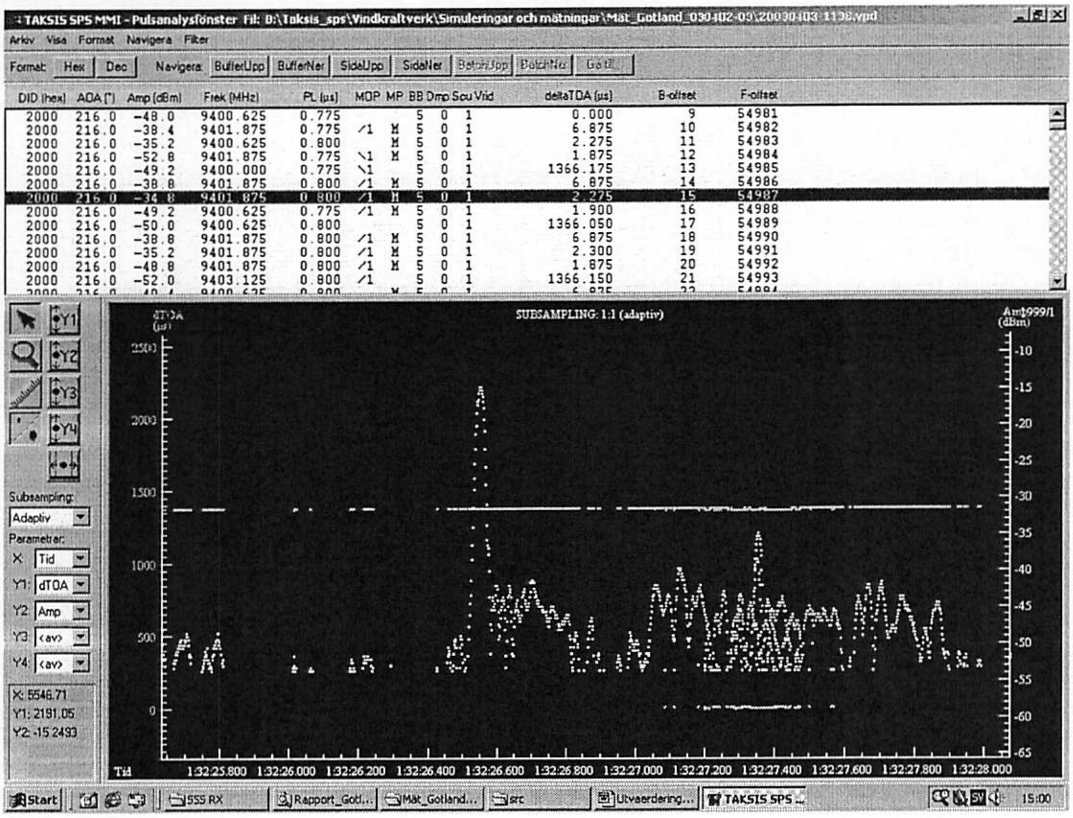


Figure 9: Näsudden - amplitude and dTOA measurements.



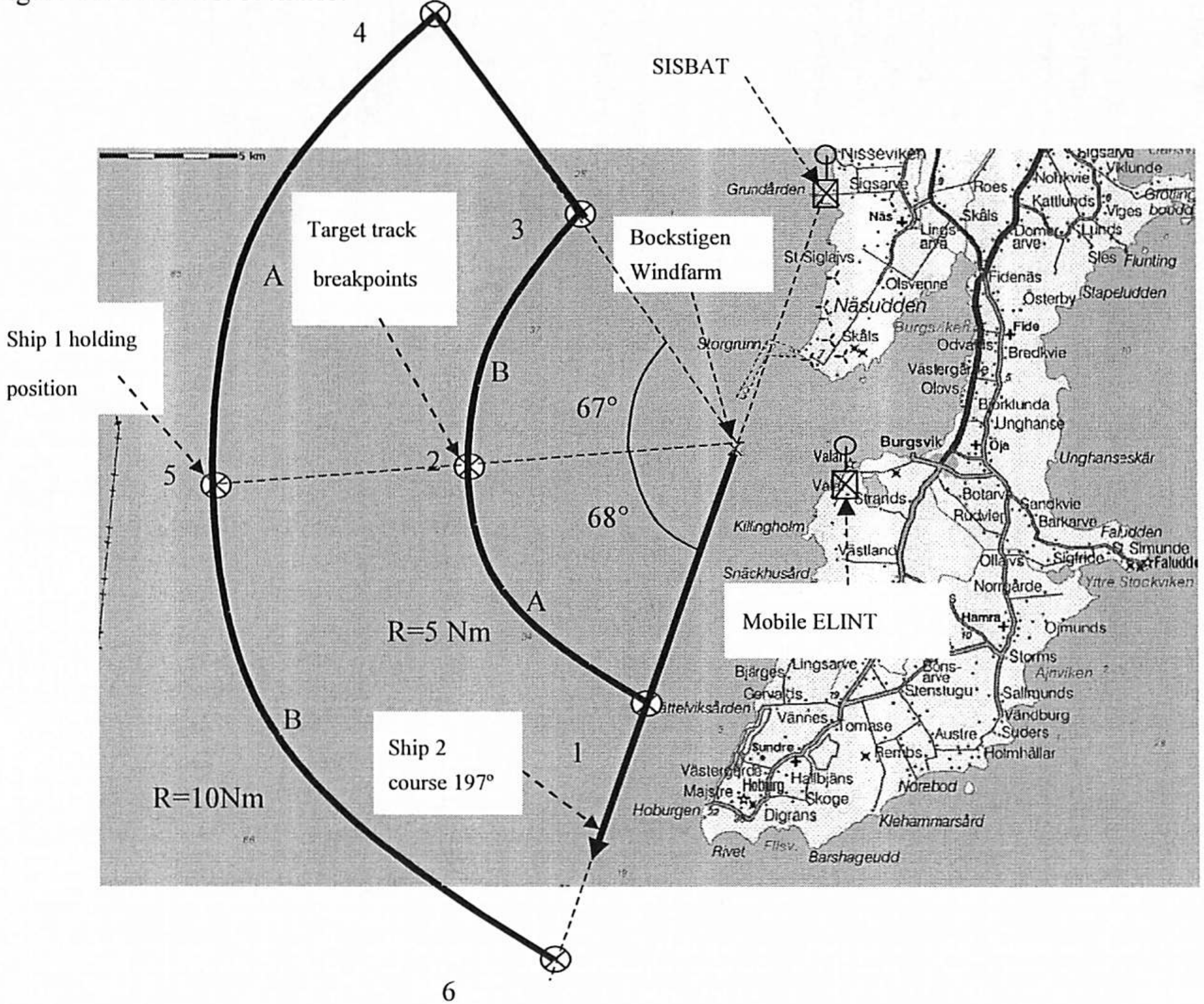
2.4.2 Field tests with modified system

A field test with the modified Swedish Army Signal Intelligence Battalion (SISBAT) was also performed at Bockstigen and Näsudden windfarms on Gotland, figure 10. The windfarms was the same as in the previous test, section 2.4.1, but the distance was longer in order to cover all windmills with the more high gain antenna. Illuminating the windmills we during the final field test used more advanced radars (modes) on the Swedish Navy Corvett Göteborg (Sundsvall) and Missile Boat Ystad.

Figure 10: SISBAT at Grundården – Näsudden.

The test scenario used is presented in figure 11. Measurement was primarily done against Bockstigen, the five offshore windmills, but also against Näsudden windfarm. SISBAT and also a mobile ELINT were located as shown in the picture. Normally the Navy ships moved as indicated by target tracks between breakpoints where all specified radar modes were emitted. We also performed a test with one ship in holding position, breakpoint 5, and the other moving at course 197° away from Bockstigen windmills. This test was done for investigating potential hiding of identical emitters.

Figure 11: Field test scenario.



The result of the final field test showed once again that the ESM system (test object) performed in real environment exactly as in the radar simulator. A difference is that real signal environment produces more false emitters since effects of multipath are greater. Observations from the test indicated that:

a) Radar pulses reflected in many windmills are shattered and create bursts of pulses with short dTOA(PRI). This is especially true if the pulses are longer than 5µs. The new algorithms in the modified system identify the reflections and marks them multipath (M).

b) Radar pulses reflected in one or few windmills don't shatter but creates a replica of the original radar pulse train. Emitters in the direction of windmills are correlated to emitters in other directions and the system gives reference to two candidate emitters in priority order.

c) A few radar emitters will not be a) marked or b) correlated. This is caused by the complexity of the emitters. They are changing signal parameters between and during illuminations. The signals can't be recognized and the change of pulse width (widened or shortened) is too large for correlation. However the amount of unmarked and uncorrelated emitters is small and they could therefore be handled by the manual ELINT operator.

Analysis of the field test is showed in table 2 below. The table shows that of a total of 476 emitters in the direction of windmills 295 (62%) were marked multipath (M), 139 (29%) was correlated and the residue was 42 (9%).

Table 2: Analysis of reflection handling algorithms.

Pulse width	**Created emitters**	**M-marked**	**Correlated**	**Residue**
Short	62	29 (42 %)	33 (48 %)	7 (10 %)
Medium	224	101 (45 %)	100 (45 %)	23 (10 %)
Long	183	165 (90 %)	6 (3 %)	12 (7 %)
Total	**476**	**295 (62 %)**	**139 (29 %)**	**42 (9 %)**

2.5 Conclusions and recommendations

The study of automatic ELINT/ESM resulted in a verified and validated signal processing modification allowing the AutoTES system to cope with reflections. Modified software was also delivered to SISBAT. Radar simulations and field testing showed that:

- reflections are mostly marked as Multipath.
- correlation is done to real emitters if the reflected signal has equivalent signal parameters.
- modifications have no negative effect on contracted technical/tactical scenario used for system delivery approval.

Observed remaining problems:

- 5 – 10 % of reflections are still propagating through the system. This small amount can be tolerated and handled by the ELINT operator.
- the modified signal processing can hide identical emitters behind the windfarm. This can only be handled by cooperating systems with coverage of the area, i.e. triangulation between two deployed systems.

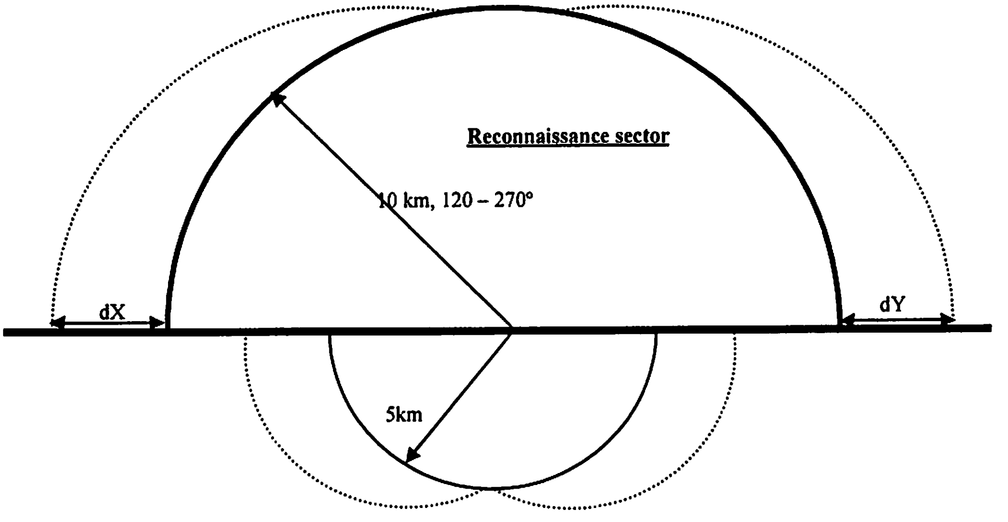
Suggestions for further algorithm improvements of the system also exist, i.e reducing the 5 – 10 % above, but they are not considered as necessary.

Ability to handle reflections is now a recommended requirement in future acquisitions for use by the Swedish Armed Forces. Reflection hardened ESM technology will, dependent on time of new investments, be used in all (fixed and remotely controlled) ELINT stations along the Swedish coast line to reduce the required protected areas. In cases where offshore windfarms are going to interfere with ELINT sites building commissioners are offered paying for the damages, i.e. for investment in the required ELINT equipment. Considering the project cost of often many billion SEK this would be a small fee for the permit.

With the new reflection hardened automatic ELINT/ESM technology we want to reduce the protection range used today. Considering the radar horizon and the fact that best place for location of windmills, i.e. greatest attenuation, always is in the middle, between the emitter and receiving systems, we have chosen the new 10 km protection range. This normally, depending of system sensitivity, will guarantee that the signal processing always detect both the direct and reflected signals. Otherwise the modified signal processing doesn't work. Shorter distances than 10 km would inevitably lead to higher signal levels for reflections and therefore increased interference. Accordingly for automatic ELINT/ESM the protection range is reduced from 100 km to 10 km when using reflection hardened systems, see figure 12. Along the cost line this means that the protected area also is reduced from about 200x100 km to 20x10 km for site location. The figure also shows an additional 5 km circular protected area needed for avoiding high detectable reflected signals in back- or sidelobes.

Regarding manual ELINT collection the study has shown that real signals in direction of windmills can be hard to separate from reflections. This is especially true in real time but also hard during off-line analysis of digital registrations. Occurrence of reflections in the frequency spectrum also tends to trigger unwanted interception i.e. locking the system and reducing available time for detection of real signals. With lots of signals in a frequency band the situation is severe. A consequence of problems mentioned above is that weak signals can be undetected considering the interference from reflections. The recommendation from the study is therefore to keep the 100 km protection range in the main reconnaissance sector for the fixed ELINT sites where manual collection take place. In other directions ESM can provide tactical coverage and tip-off to the manual ELINT operator, i.e. with reduced protection range of 10 km.

Figure 12: Protected area around tactical ELINT stations.



dX+ dY = required uncertainty regarding wartime sites.

3. COMMUNICATION INTELLIGENCE SYSTEMS

3.1 Introduction to radio direction fining (DF) study

Protection of communication intelligence (COMINT) from effects of windmills in the frequency ranges HF, VHF and UHF is based on radio direction finding (DF). The main reason for this is that under normal circumstances detection and demodulation, i.e. capturing signal message content, is not a problem because of the big difference in signal levels between direct and reflected signals, but of course exceptions exist.

Many radio DF methods exists for example Adcock, Watson-Watt, interferometer or in general phase measuring systems. Accuracy of DF in practical use is usually less than specified or in laboratory conditions proven by the manufacture. Typically strategic DF have an accuracy of $\leq 1°$ rms and tactical DF $\leq 2°$ rms.

Calculating the effect on radio DF sites (point of observation) in the geography with one or more at different distances located windmills with equal or different dimensions is a very complex problem not possible to solve with analytical methods. Development of computer power and electromagnetic solvers provide means to do this kind of calculations today. FRA therefore decided in 1998 to sub-contract the Swedish Defence Research Agency (FOI) to do this part of the study since they have the tools and very high competence in the subject field. The FOI report "Direction finding error due to scattering from windmills, analysis and computations" in appendix 1describes in more detail the results of this work.

3.2 DF error model and windfram scenario calculations

FOI has developed a model for estimation of direction finding (DF) errors based on a 3-channel phase DF system. In this case the antenna elements of the array are connected by a (ideal) network, Butler matrix, resulting in a multi-lobe antenna with three ports (probes) labelled +1, -1 and 0. Direction finding errors mainly depend on the gradient of the radiowave phase front, which in our case is influenced by scattering objects (windmills) in the vicinity of the DF system. The equation for the DF error model, see appendix 1 chapter 2, is presented bellow:

$$\Delta^{rms}{}_{+1/-1} \approx 2^{-1/2} * (\Sigma_\mu | \xi (| r^{bar}{}_\mu - r^{bar}(P) |, \varphi_\mu , \varphi_s , f)|^2 \ |\sin(\varphi_\mu - \varphi_s|^2))^{1/2}$$

$RSC = \sigma(\varphi, \varphi_s, f) = \lim_{\rho \to \infty} 4\pi\rho^2 | \xi(\rho, \varphi, \varphi_s, f)|^2$

$\xi(\rho, \varphi, \varphi_s, f)$ = scattered electromagnetic field

r = point of the electromagnetic field

P = point of observation = (ρ, φ)

ρ = distance between scattering object and P

φ_s = incidence angle of electromagnetic field

φ_μ = object angle

f = radio frequency

Unique properties of this error model is that it allows calculating rms errors for many simultaneous types of scattering objects (windmills) at different distances. The equation can also be used to calculate successive approvals for a specific radio DF site, i.e. geographic area. The equation is more relevant for higher frequencies and large number of windmills located in preferably irregular patterns. Considering the latter, regular patterns can generate constructive interference and therefore the irregularity should be at least half the wavelength. Also at least 5 rotor diameters should be used between windmills since otherwise effects of second order or reflections will increase.

Frequency range in the study was HF (2- 39 MHz) and VHF (30 – 300 MHz). On HF the wavelength, $\lambda = c/f$, is of the same order as the windmills and Radar Cross Section is in the resonant area. VHF produces a more stable RCS. Doing DF error calculations FOI usually stopped at 50 MHz even if some complementary calculations was executed up to 250 MHz. The reason for this was that at 300 MHz you need to sample the electromagnetic field 10 times faster than at 30 MHz, and with available computer power the calculations would have taken many weeks. In the study also the worst case scenario with surface wave propagation, 0° horizontal depression (elevation) angle, was chosen.

Windfarm scenario used by FOI is shown in appendix 1 section 3.4 figure 3.5. The area of the windfarm is about 2.5 x 1.0 km with nineteen 80 meters windmills placed in a pattern of 5 rotor diameters in the x-direction and 7 rotor diameters in the y-axis.

FOI has shown that top and rms errors are about the same at 2 MHz and 50 MHz but more random on higher frequencies, see appendix 1 section 3.5 figure 3.6. To be observed is that the incidence angle for maximum rms error is frequency dependent, se appendix 1 section 3.3 figure 3.4. At 2 MHz maximum occur at 90° and with higher frequencies the angle decreases. Based on the study results we can assume a generic error model valid for HF, VHF and probably also on UHF.

Appendix 1 also shows computer calculations (at 20 MHz) of direction finding errors in section 3.5 figure 3.7. Radio DF is located 5 km from the windfarm and emitters are located in different incidence angles at 5, 10, 50 km and infinite (still within radio horizon) distance from the group of windmills. Figure 3.7 shows that at 10 km and 0° incidence angle the minimum rms error is about 0.9°. If the distance is increased to 50 km the error decrease to 0.4° . At 50 km and infinite emitter distance the difference between rms errors are small for all incidence angles. Estimated statistical properties in figure 3.7 are shown in table 3 below. Distance ∞ km of course means that the signal still can be detected.

Table 3: Estimated statistical properties.

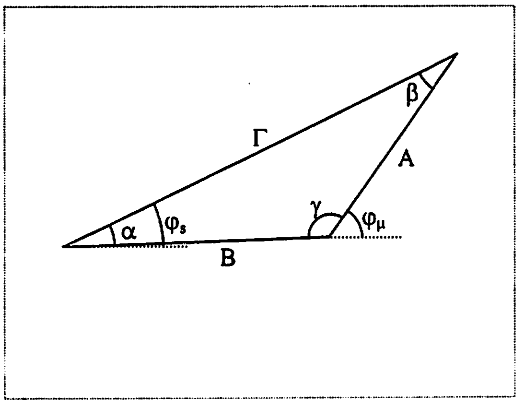
RMS error [°]	Distance 5 km	Distance 10 km	Distance 50 km	Distance ∞ km
Maximum	3,6	2,7	2,2	2,1
Mean	2,6	1.9	1,5	1,4
Minimum	1,6	0,9	0,4	0,4

3.3 Simplified DF error model

The FOI study has resulted in executable software for estimation of direction finding errors using the commercial products FEMAP (CAD software), FEKO (electromagnetic solver) and MATLAB. No contract has yet been issued from the Swedish Armed Forces to buy this software package. Taking software license into account and the fact that clerks handling windmill building applications don't have knowledge enough to use the tools FRA decided to create a simplified model implemented in MS Excel, presented below.

A model for protection range between radio DF system and windmills can be obtained if the receiver (radio DF) and the emitter change locations in figure 3.7 appendix 1. The emitter is then located at 5 km distance from windmills. If one would like to switch places between the receiver and the emitter in the equation of DF error, then ξ (scattered electromagnetic field) is unchanged due to reciprocity, and the angle $(\varphi_\mu - \varphi_s) = \beta$ is changed to α, according to figure 13 below.

Figure 13: Incidence angle of electromagnetic field (φ_s) and object angle (φ_μ).



In the equation for DF error, each term is multiplied with the factor $\frac{\sin(\alpha)}{\sin(\beta)}$

Since $\frac{\sin(\alpha)}{A} = \frac{\sin(\beta)}{B} = \frac{\sin(\gamma)}{\Gamma}$ it follows that $\frac{\sin(\alpha)}{\sin(\beta)} = \frac{A}{B}$

If the distance between scattering objects is small compared to the distances to receiver and emitters, A and B is regarded constant and the correction factor can be calculated outside the DF error equation. Table 4 shows the result of the transformation of table 2 and also the contribution of single windmills. Values for 20, 30 and 40 km are interpolated between 10 and 50 km.

Table 4: DF errors at different protection ranges.

RMS error [°]	5 km	10 km	20 km	30 km	40 km	≥ 50 km
Mean	5.2	1.9	0.9	0.57	0.40	0.3
Mean/sqrt(19)	1.19	0.44	0.21	0.13	0.092	0.069

The total DF error = $(\Sigma(n * \varepsilon_m^2))^{1/2}$, where n = number of objects, m = distance to nearest object and single windmills error contribution (ε_m) is fetched from table 4. Beyond 50 km the most distant windmill to take into account on VHF/UHF is defined by the radio horizon, defined below. HF DF range is not limited by receiving Ionospheric propagation rather communication via ground-wave propagation which is limited to about 300 - 400 km, depending on sea water salinity. In this case a reasonable distance therefore should be considered.

Radar/radio horizon = $4.1 * (h_1^{1/2} + h_2^{1/2})$ [km]

h_1 = receiver antenna height [m]
h_2 = emitter antenna height [m]

In general our building approval model allows windmills or other scattering objects if the calculated total DF rms error is less than or equal to the instrumented rms error of the radio DF equipment. But the model found above only applies for windmills with a height of 80 m, used by FOI in computer calculations. Therefore we must compensate for other tower heights.

We know that for a cylindrical structure (like the windmill tower) the RCS (σ) equation can be approximated by:

$$\sigma = 2 * \pi * L^2 * a * \cos(\beta/2) / \lambda \sim k * L^2$$

L^2 can be assumed if the tower radius (a), nacelle (rectangular box) and blades contribution is relative constant.

Another factor to take into account is that modern advanced digital direction finding systems sometimes have adaptive beamforming and interference (jamming) rejection, i.e. the ability to attenuate effects of jamming from a number of sources doing DF in other directions. Even with this technique error contributions remains in the interfering directions but perhaps not in important directions and causing maximum error, se section 3.2. Attenuation can be expressed in dB. A change of 6 dB is double or half the distance (ρ).

Using the radar equation it could be shown that:

$$P \sim L^2 / \rho^2 \text{ [W]}$$

Summing-up this relation gives us an opportunity to calculate an equivalent distance for reasonable change of tower height and/or DF with interference rejection. Correction is simply done by using the equivalent distance when object error contribution (ε_m) is fetched from table 4. Of course by doing linear interpolation we also can find all values in between.

3.4 Approval procedure using the simplified DF error model

The simplified model developed in section 3.3, has been implemented in MS Excel and is used in the following 9 step building approval procedure.

Keeping data for every DF site:

1) For every DF site an Excel table is created and new applications can then be added to earlier approved ones.

2) Instrumented radio DF error [$\varepsilon°$] shall be defined for the site.

3) Radio DF interference rejection capability shall be defined in dB for the site.

Data for new windmill applications:

4) Distance to the nearest object in km within radar horizon.

5) Number of objects.

6) Tower height to turbine axis, i.e. rotor boss.

Decision Yes or No:

7) If the distance is less then a 5 km circle from radio DF the application is rejected.

8) If calculated total error is less or equal to instrumented DF error the application is approved.

9) If application is not approved it could be considered (together with the building commissioner) if change of distance, number of objects or change of height could result in another decision.

Appendix 1: Direction finding error due to scattering from windmills, analysis and computations.

This part of the document is provided as a separate pdf file.

Authors: Tomas Boman, Leif Pettersson

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Division of Sensor Technology
SE - 581 11 LINKÖPING

FOI file code: FOA-R—00-01522-616—SE
May 2000, ISSN 1104-9154

The National Defence Radio Establishment presentation. IEA R&D Expert Meeting on Radar, Radio, Radio Links and Wind Turbines, London, 17 – 18 March 2005.

Directive of the study: Investigate effects on signal intelligence (SIGINT) from large-scale offshore windfarms. Also investigate the possibility of technical modifications to minimize interference from windmills.

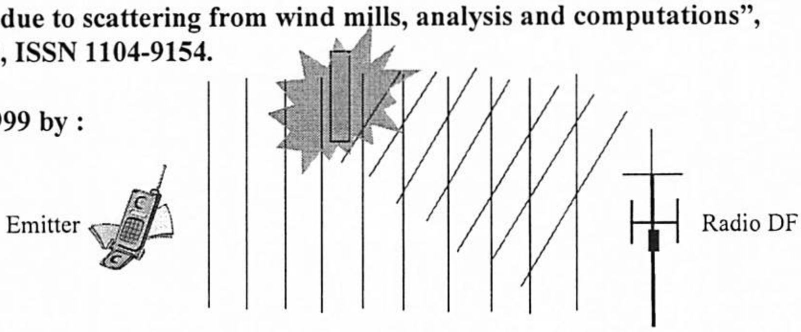
RADIO DIRECTION FINDING STUDY

The Swedish Defence Research Agency was sub-contracted the study of Direction Finding.

Study report: "Direction finding error due to scattering from wind mills, analysis and computations", FOA-R—0001522-616—SE, May 2000, ISSN 1104-9154.

The study was carried through 1998-1999 by :

Tomas Boman, researcher
Leif Pettersson, researcher
Hans Frennberg, project leader



Activities:

1) **Analysis of scattering from groups of windmills and there effects on traditional DF systems.**

2) **Development of DF error model for single or groups of windmills at different distances. Implementation of the new DF error model in Matlab.**

3) **Electromagnetic field calculation for a windfarm scenario with simple geometry.**
   - Description of 25, 50, 80 m windmills in FEMAP CAD software.
   - Field calculations done by using FEKO electromagnetic solver.

4) **Radar cross section calculation of single windmills at HF (2-30 MHz) and VHF (30 -300 MHz).**

MODEL FOR DF ERRORS

The study has chosen a model with a 3-channel phase DF system. Butler matrix with probes (+1,-1 and 0) is connected through the ideal network to an infinitesimal circular antenna array.

Direction finding error equation for single objects:

$$\Delta_{-1/-1} = 0.5\arg\left(\frac{1+e^{i\bar{k}_{in}\cdot\bar{r}(P)}\xi(P,\varphi_s,f)e^{i(\varphi-\varphi_s)}}{1+e^{i\bar{k}_{in}\cdot\bar{r}(P)}\xi(P,\varphi_s,f)e^{-i(\varphi-\varphi_s)}}\right). \qquad (2.5)$$

Direction finding equation for groups of objects

$$\Delta_{-1/-1} = 0.5\arg\left(\frac{1+\sum_{\mu} e^{-i\bar{k}_{in}\cdot(\bar{r}_{\mu}-\bar{r}(P))}\xi(|\bar{r}_{\mu}-\bar{r}(P)|,\varphi_{\mu},\varphi_s,f)e^{i(\varphi_{\mu}-\varphi_s)}}{1+\sum_{\mu} e^{-i\bar{k}_{in}\cdot(\bar{r}_{\mu}-\bar{r}(P))}\xi(|\bar{r}_{\mu}-\bar{r}(P)|,\varphi_{\mu},\varphi_s,f)e^{-i(\varphi_{\mu}-\varphi_s)}}\right). \qquad (2.12)$$

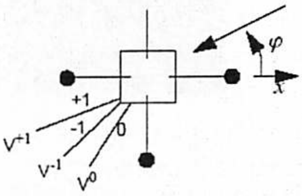
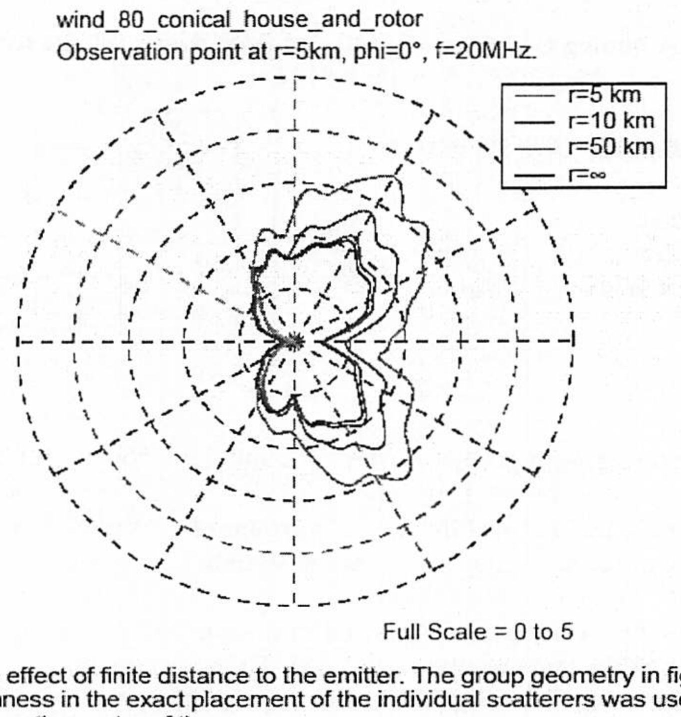


Figure 1.3 Phase direction finder antenna.

DF ERRORS RMS



Mean error rms

5 km : 2,6°
10 km : 1,9°
50 km : 1,5°
∞ km : 1,4°

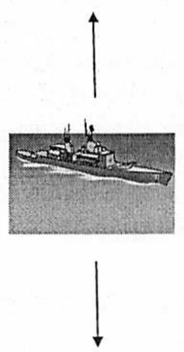
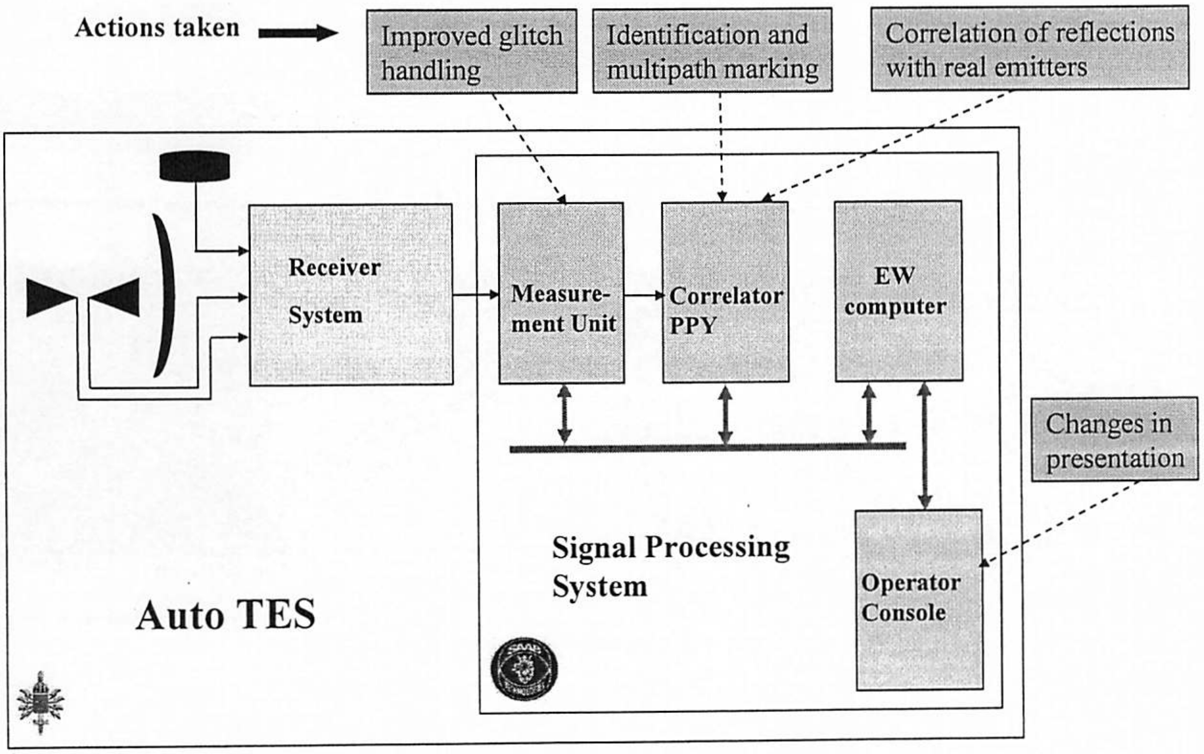


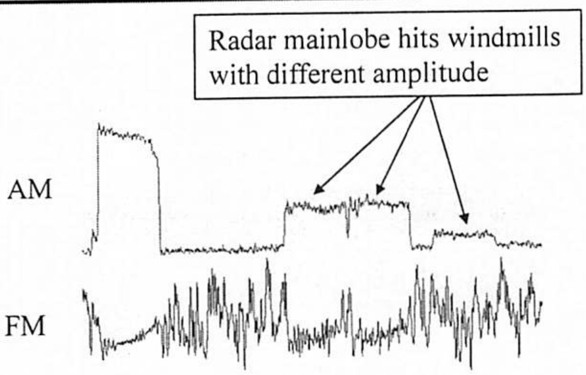
Figure 3.7 The effect of finite distance to the emitter. The group geometry in figure Figure 3.5 c, with some randomness in the exact placement of the individual scatterers was used. The distances were measured from the centre of the group.

MODIFIED AUTO TES

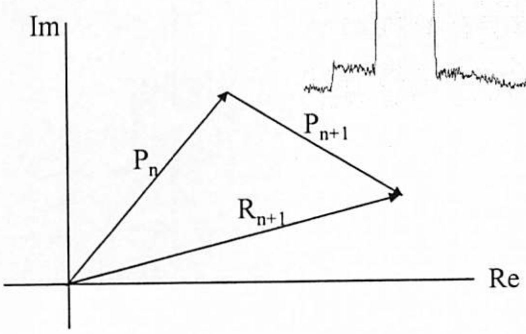


CHARACTERISTICS OF REFLCETED SIGNALS

Case 1: A radar identical signal is created by reflections in individual windmills by a narrow antenna mainlobe.

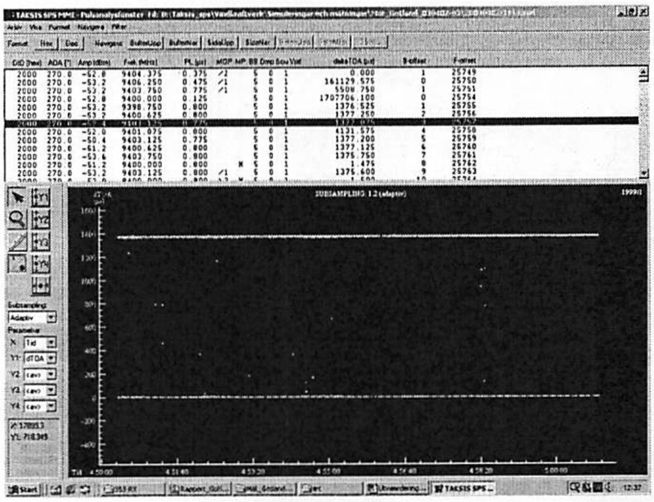


Case 2: A burst of pulses is created by successive and/or parallel reflections in different windmills. False Pulse Repetition Interval (PRI) values are created. The right picture shows direct pulse and three measured reflections. The last pulse has low amplitude and therefore bad FM.

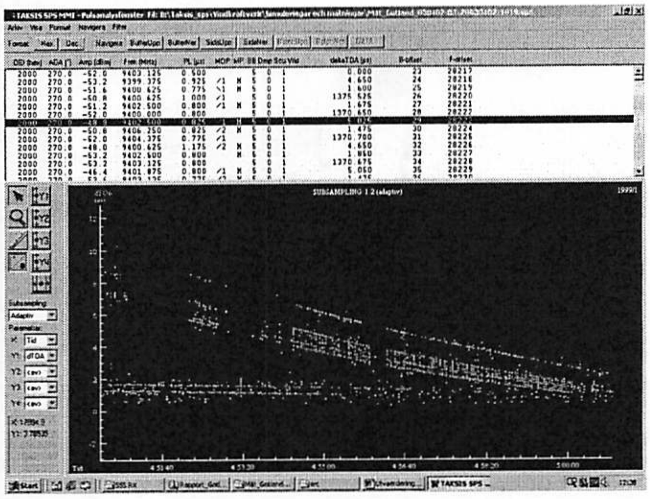


Case 3: Pulseoverlap. Jω-diagram left shows that a resultant R_{n+1} is created by vector addition of pulse P_n and P_{n+1}. Depending on different time of propagation the resultant gets arbitrary amplitude and phase. The picture also shows three overlapping measured pulses.

FIELD TEST 1 WITH UNMODIFIED ESM SYSTEM



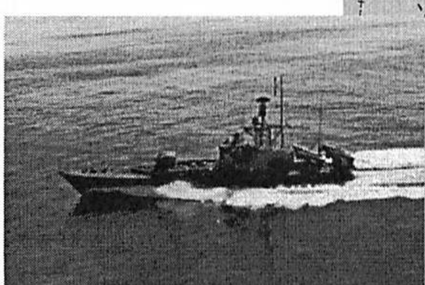
Reflected signal with PRI 1377 μs at the top and synthetic PRI (dTOA) above 0 μs.



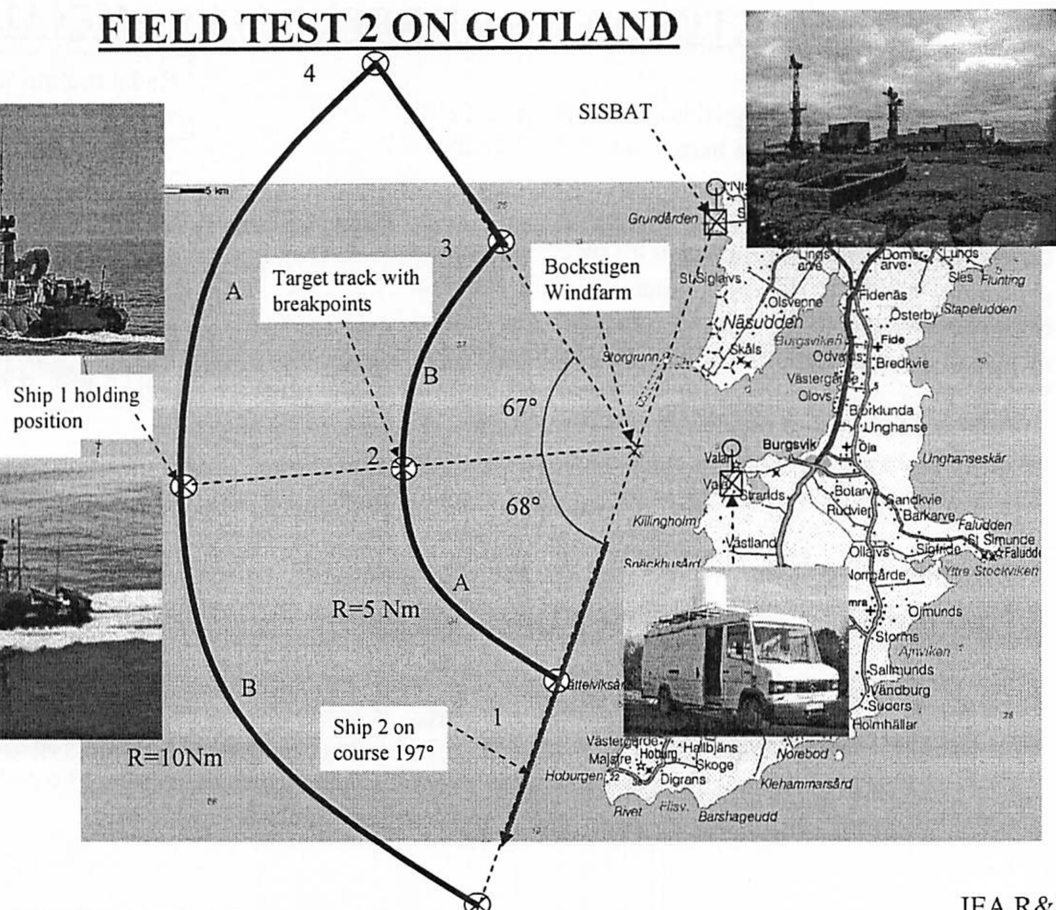
Synthetic PRI on expanded time axis.

FIELD TEST 2 ON GOTLAND

Corvett Gothenburg



Missile Boat Ystad



RESULT OF THE STUDY

Study result showed:

a) reflections are mostly marked Multipath.

b) correlation is done to real emitters if the reflected signal has equivalent signal parameters.

c) no negative effect regarding technical/tactical scenario used for system delivery approval.

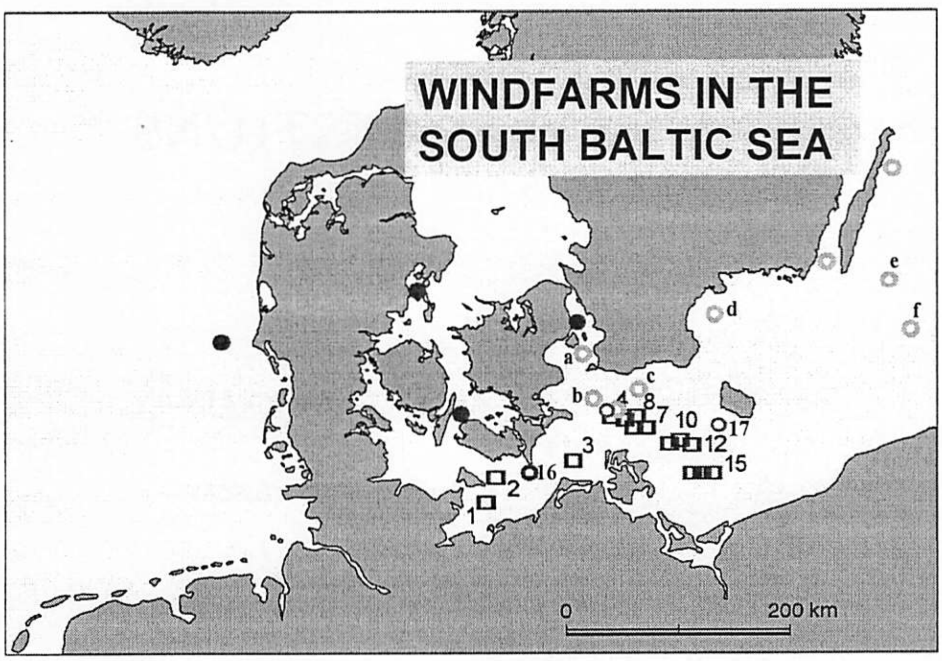
Observed remaining problems:

d) 5 – 10 % of reflections still propagate through the system => handled by the ELINT operator.

e) processing can hide identical emitters behind the windfarm => solved by triangulation.

Conclusions:

SIGINT tactical reporting of surface and air targets in real time can be secured by ESM if the systems has reflection hardened capability and the right geographical deployment.



WINDMILL COSTS (Elforsk AB):
Land based : 495 – 708 £/kW
Sea based : 1000 – 1168 £/kW

4 MW = £ 4M

Life span: 20 years

Planed to year 2007:

Swedish:
4= Kriegers Flak Sweden Offshore 128 pcs (640 MW)

German:
1= Sky 2000 (150 MW)
2=Beltsee Plambeck (415 MW)
3= Baltic I 21 pcs (42 MW)
4=Kriegers Flak WPD/Wind-projekt 75 pcs (315 MW)
5–10=Vento Tec ost II (600 M)
11=Arkona bäckenet sydost (945 MW)
12=Adler grund (790 MW)
13–15=Pommerska bukten (1 000MW)

Danish:
4 = Kriegers Flak 30 - 50 pcs (150 MW)
16= Rödsand, Nystedt, Lolland (158 MW)
17 = Rönne Banke

Other Swedish areas suitable for windfarms
a= Örestad (Lillegrund) 48 pcs
b= Skåre – Falsterbo
c= Abbekås
d= Hanöbukten
e & f= North & South Midsjöbankarna

ADAPTION TO WINDFARMS

Required investments:

1) Reflection hardened automatic ELINT/ESM installed in fixed and ship SIGINT stations.

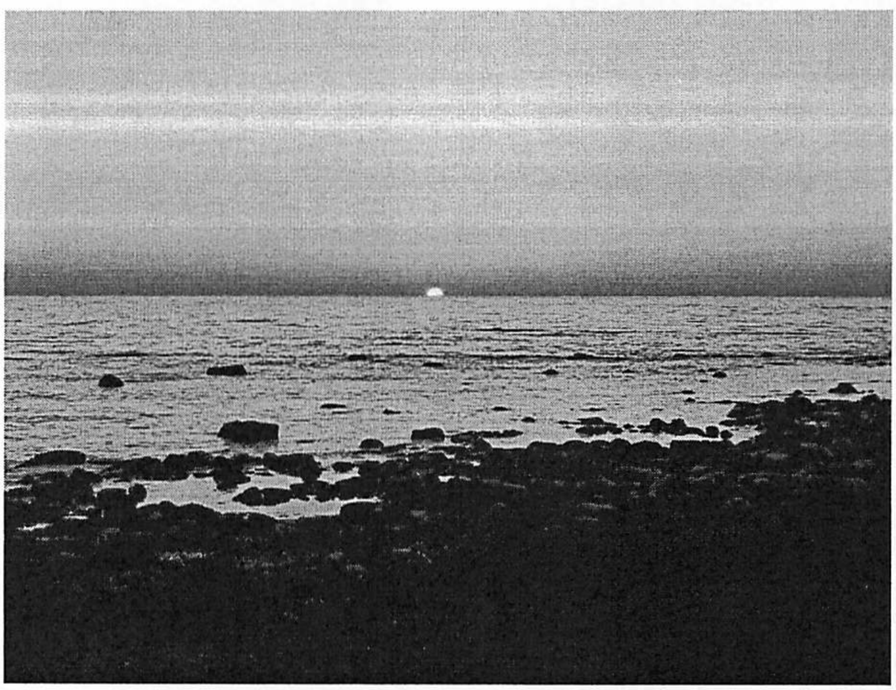
2) Deployment of two additional container based reflection hardened AutoTES at the coast-line.

Investments gives good opportunities to build offshore windfarms in the south Baltic Sea.

Government investments take long time with shrinking defence budget and focus on international peace support operations. Considering windfarm project cost of often many billion SEK faster investments can be made if windfarm projects also can contribute to financing.

Model for financing:

Windfarm building commissioners are offered paying for the damages on government intelligence and reconnaissance systems, i.e. investment in new SIGINT equipment, as a condition for building in a specific geographical area.



QUESTIONS ?

POINT OF CONTACT

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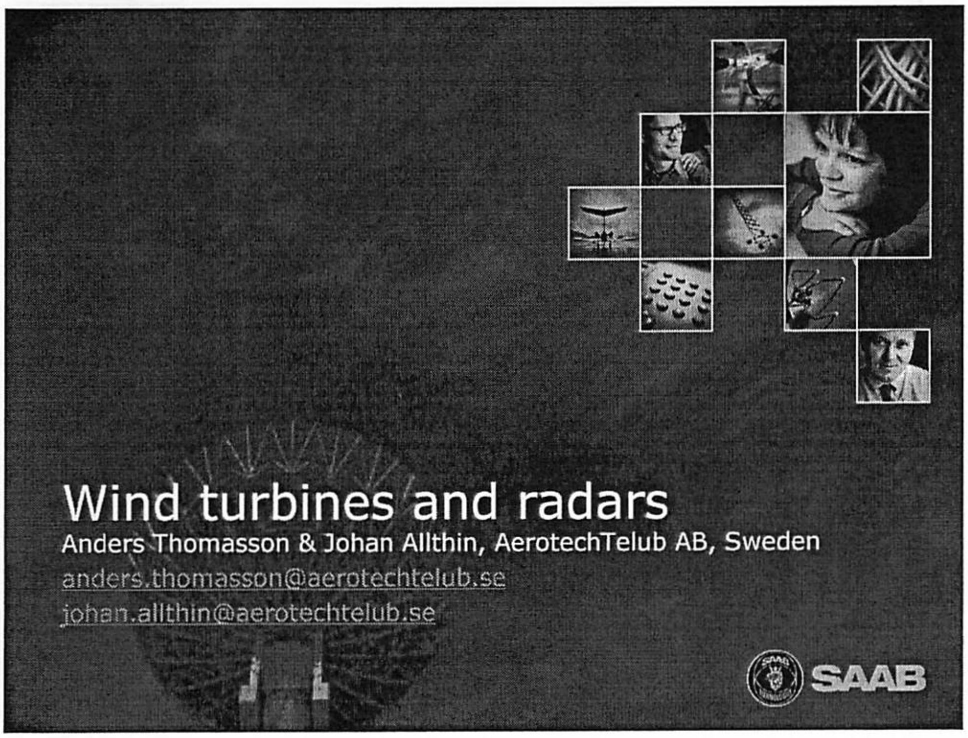
Regarding DF also

tomas.boman@foi.se



AerotechTelub

- 2 300 million SEK turnover
- 2 200 employees
- Locations: Arboga, Linköping, Växjö, Stockholm, Östersund and 11 other locations in Sweden
- A company in the Saab Group

AerotechTelub SAAB

AerotechTelub, Communications

Our range of services includes:

- Studies
- Analyses
- Specifications
- System solutions
- Control and commissioning
- Tests
- Reliability solutions
- Maintenance solutions
- Operational support
- Verification and validation
- Repairs and modifications
- Development of hardware and software

Wind Turbine Activities

- Implemented model developed by FOI, the Swedish Defence Research Agency
- Integrated with existing radio spectrum management software, WRAP (www.wrap.se)
- Integrated with existing flight obstacle database

The Implemented Model

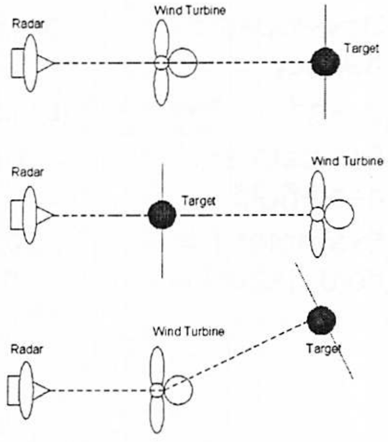
- Developed by FOI, the Swedish Defence Research Agency
- Based on Physical Optics, PO
- Far-field and near-field effects, in practice always near-field.
- Example: f = 10 GHz, tower height 100 m => Far field distance ≥ 667 km

The Implemented Model, cont'd

- The structures are approximated by simple geometrical structures
  - Tower approximated by a cylinder
  - Hub is neglected
  - Rotor blades approximated with elliptical cylinder

The Implemented Model, cont'd

- Simulated target (aircraft) moving at a fixed distance from radar
- Forward, backward (monostatic) and bistatic scattering
- Calculates undesired signal
  - Radar – Target – Wind Turbine – Radar
  - Radar – Wind Turbine - Target – Radar
  - Radar – Wind Turbine – Target – Wind Turbine – Radar
- Compares with desired signal

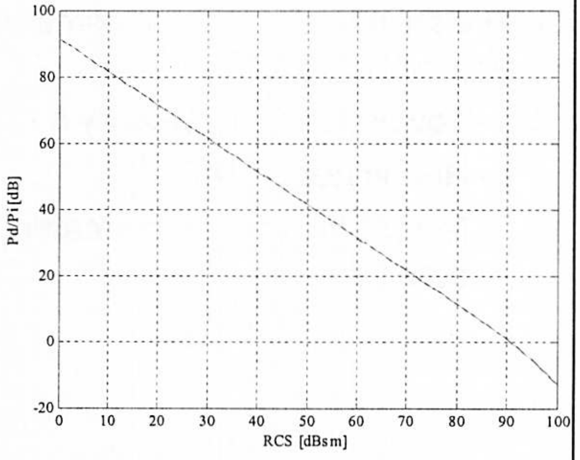


AerotechTelub

SAAB

Calculation example

- Distance radar-simulated target 60 km
- Distance radar – wind turbine 30 km
- Distance wind turbine – simulated target 30 km



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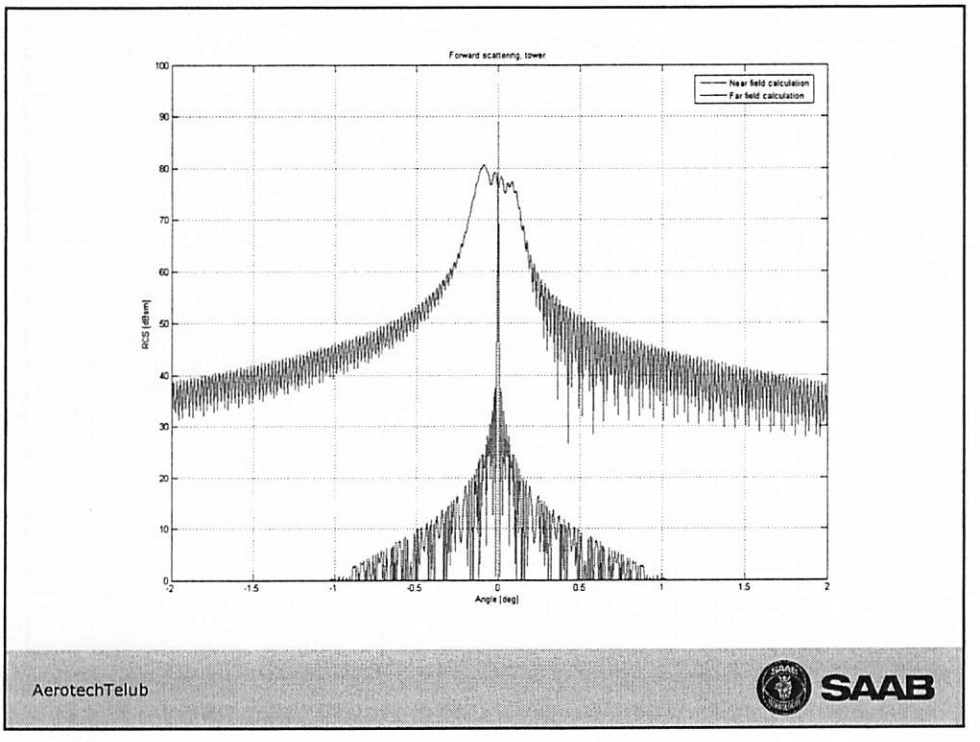
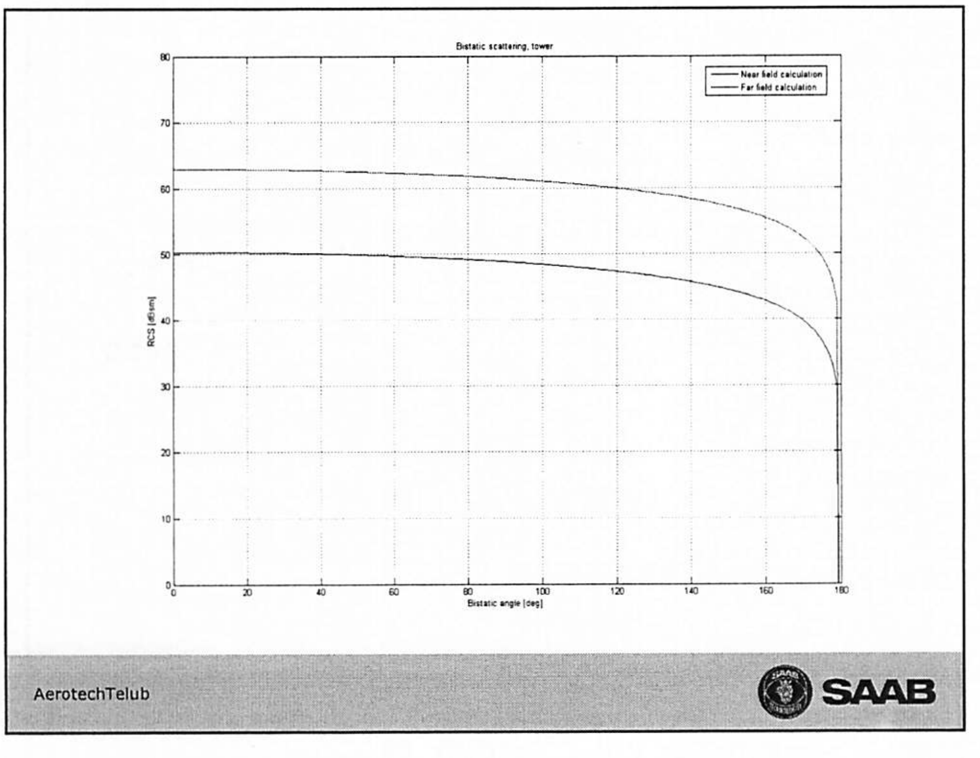
SAAB


Forward scattering, tower
Near field calculation
Far field calculation
RCS [dBsm]
Angle [deg]
AerotechTelub
SAAB


Bistatic scattering, tower
Near field calculation
Far field calculation
RCS [dBsm]
Bistatic angle [deg]
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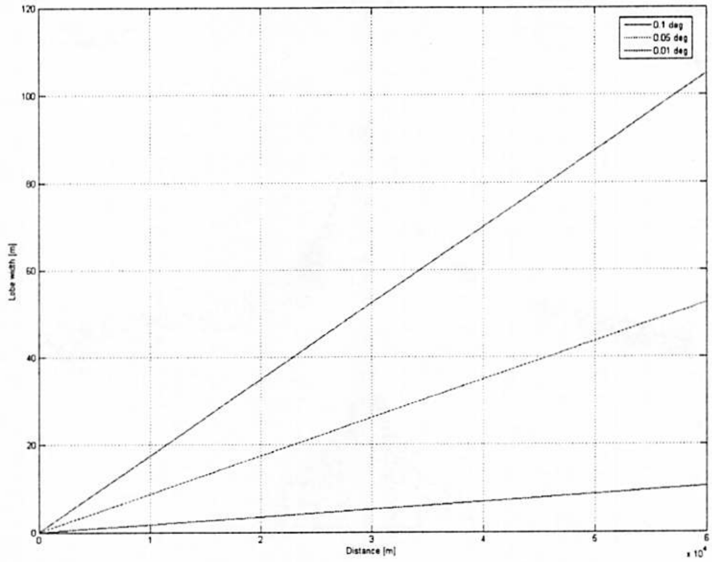
SAAB



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The Implemented Model, cont'd

- Worst case implemented
- Group effects by incoherent summation of power from individual wind turbines
- Calculation model and measurements correspond well

AerotechTelub

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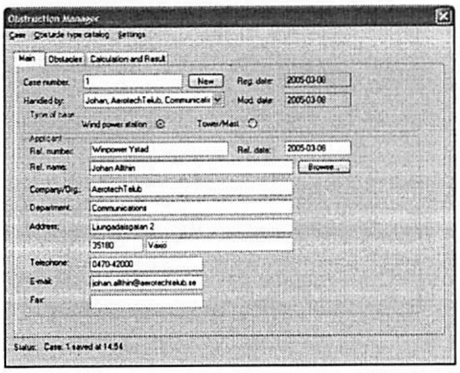
ObsMan

- WRAP is a Spectrum Management Software
- New function called ObsMan (**Obs**truction **Man**ager)
- The user states applicant information and which type of obstacle (wind power station or tower) the application is for



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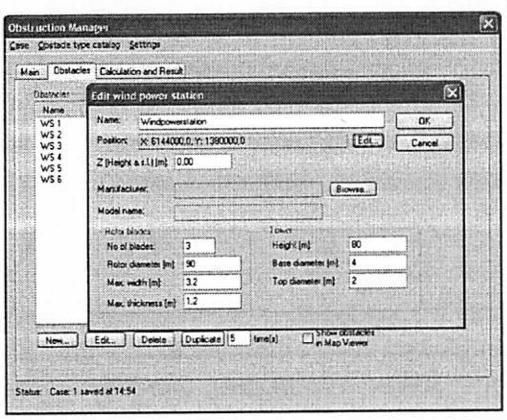
ObsMan, Obstacles

- ObsMan automatically sets ground height for the obstacle when the position is entered (based on the terrain raster dB)
- Possible to store dimensions for different manufactures/models of wind turbines in the ObsMan database



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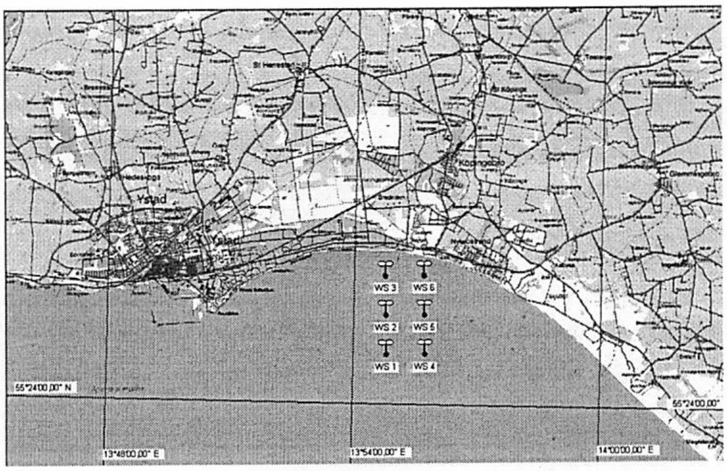
ObsMan, Obstacles, cont'd



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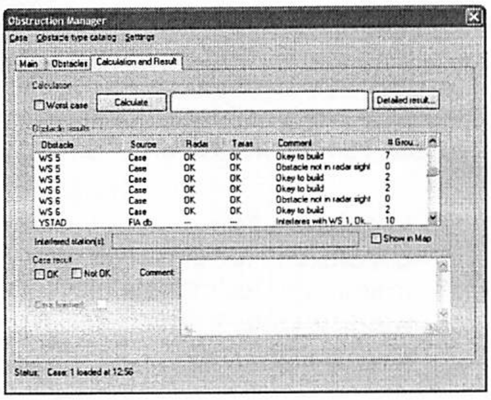
ObsMan, Calculation and Result

- Already built wind turbines and towers are included in the calculation
- Terrain blocking is taken into account in the calculation (Radar -> obstacle)
- The user receives a recommendation ("Okey to build" or "Not okey to build")



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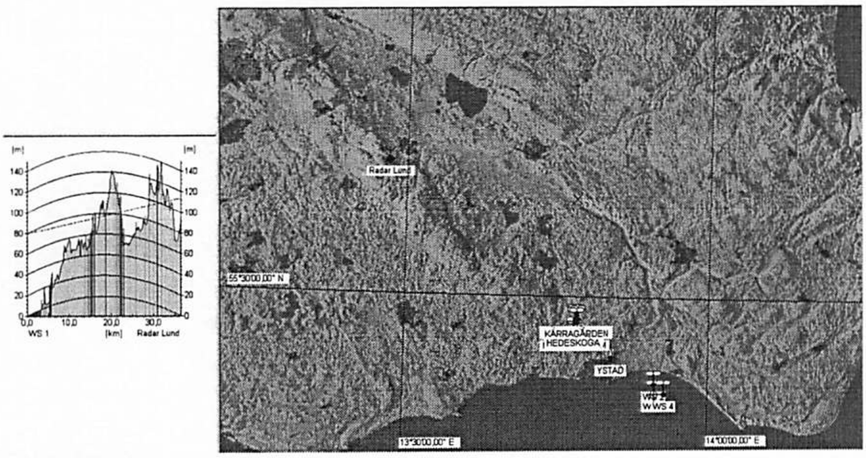
SAAB

ObsMan, Calculation and Result, cont'd



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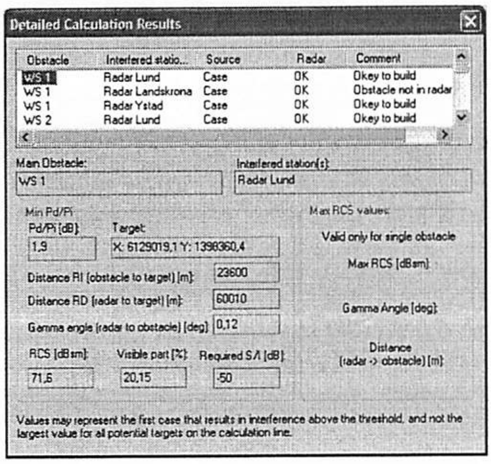
ObsMan, Calculation and Result, cont'd

- Possible to get detailed calculation results for further analysis



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SAAB

Summary

- Positive:
  - + Model and measurements correspond
  - + Terrain blocking is taken into account
  - + Easy to use, anyone can use it (no knowledge of radar cross section calculations required)
- Negative:
  - – Sensitive to input parameters
  - – Worst case calculation results may be too negative
  - – Slow when calculating large numbers of obstacles (i.e. large groups wind power stations)

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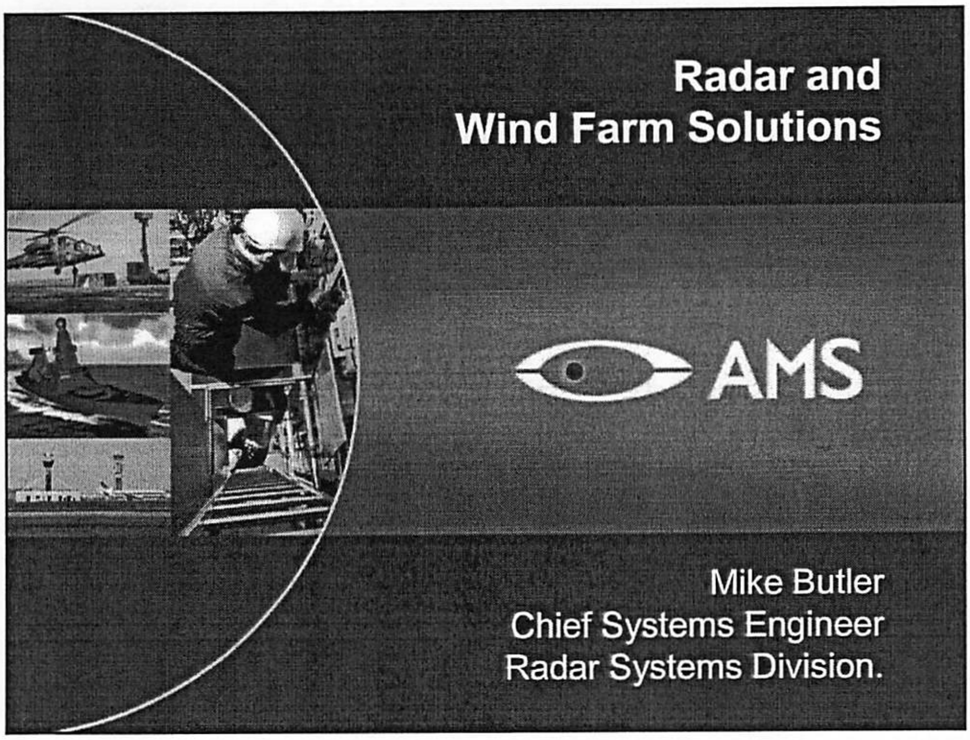
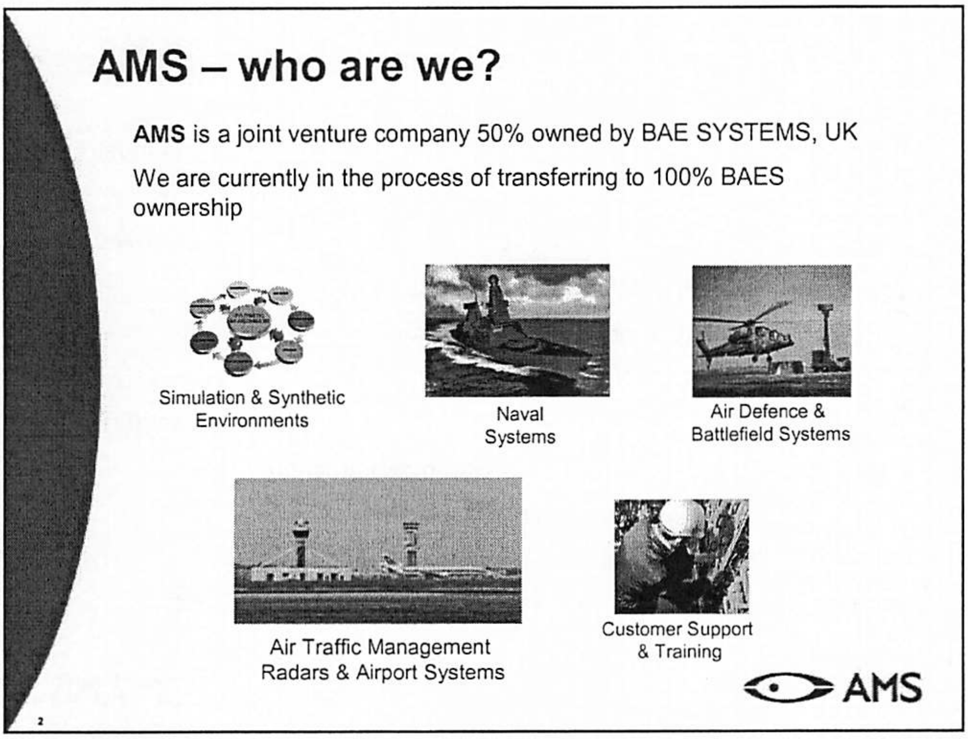
SAAB


Radar and
Wind Farm Solutions
AMS
Mike Butler
Chief Systems Engineer
Radar Systems Division.


AMS – who are we?
AMS is a joint venture company 50% owned by BAE SYSTEMS, UK
We are currently in the process of transferring to 100% BAES ownership
Simulation & Synthetic Environments
Naval Systems
Air Defence & Battlefield Systems
Air Traffic Management Radars & Airport Systems
Customer Support & Training
AMS
2

AMS - radar division

- The sole UK designers and manufacturers of long-range radar systems
  - Naval:
    - Surveillance radar
    - Target Indication Radar
    - Tracking Radar (missile guidance)
    - Multi-Function Radars
  - Air Traffic Control Radar
    - Civil and military
  - Land Based Military Air Defence
  - Land Based Mobile Surveillance and Tracking
  - Over-the-Horizon (EEZ)
- Working on wind farm issues for the last 3 years

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3

AMS Current Wind Farm Activities

- Development of the 'Wind Farm Toolbox' for Wind Farm Industry
- Significant Investment in Advanced Digital Tracker (ADT)
- 'Radar Partnering' with Developers from early phases of project
- Close working relationship with BWEA
- Support to Government Working Groups
- Supporting RAF Wind Farm Trials
- Conducting 'The Wash' Air Defence Radar Study Contract (DTI)
- Formal ADT Demo Proposal - contract imminent.
- Industry Pricing Model being developed
- Turbine RCS Model – proposal to be submitted to DTI
- Wind farm impact assessment models being developed

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4

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The Radar Problem Summary

- Known effects of wind farms on radar:
  - **False Alarms (Detections)** caused by rotating blades breaking through the Doppler processing channels
  - **Reduced sensitivity** caused by extremely large bulk RCS of turbine components
- Effects are variable over time
  - Radar PRI strobes with turbine rotation
  - Blade flash is highly directional
  - Wind direction affects the aspect angle of the turbines blades to the radar
  - Bending and deflection of structures with wind speed modifies their characteristics
- Magnitudes of effects are dependent on many factors

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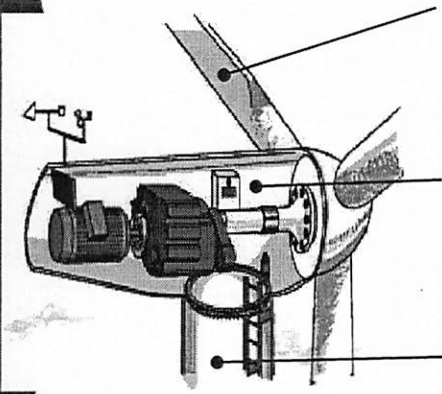
5

Radar characteristics of turbines

- Three main components to consider:



Blades:
- 45m long, 2.5m wide
- Tip speed of >50m/sec
- Future >65 m long, >100m/sec
- Typically weigh 62 Tonnes with hub

Nacelle:

•Complex shapes and moving components.

•GRP housing is radar transparent

•Typically weighs 68 Tonnes

Tower:

•Steel cylinder 100m high, 5m diameter

•Typically weighs 162 Tonnes

Figures typical of a current 2MW turbine

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6

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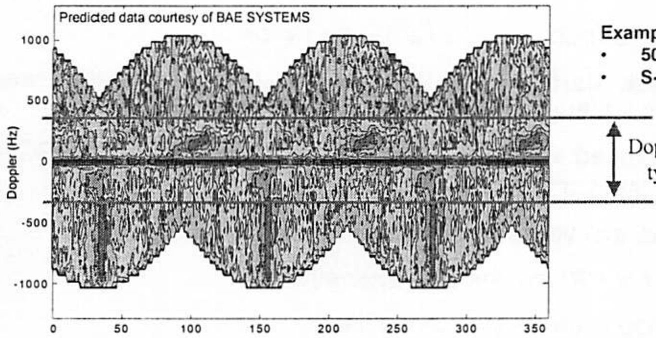
Doppler



Example:
- **50m/sec tip speed**
- **S-Band radar**

- Variability due to turbine designs and operating conditions
- Future trends to higher tip speeds, especially offshore where acoustic noise is less of a problem
- Trend towards variable rotation speed

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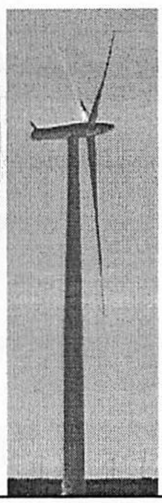
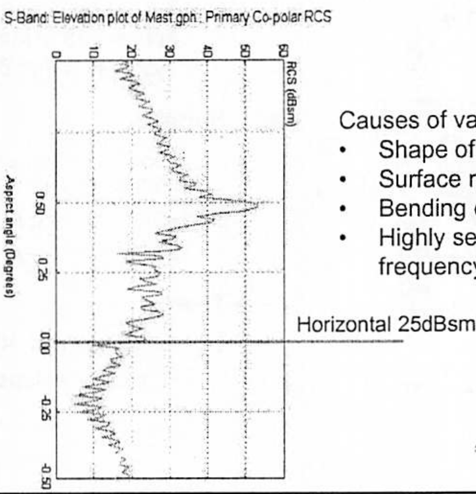
7

Characteristics: Tower

- Theoretical peak RCS of a 100m tower is 3 million square metres (65dBsm) at S-Band
- Typical reported figure 30dBsm = 1000 m² – why?

$$\sigma_{\max} = 2\pi \frac{r.h^2}{\lambda}$$





Causes of variability:
- Shape of tower
- Surface roughness
- Bending due to wind forces
- Highly sensitive to radar frequency

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8

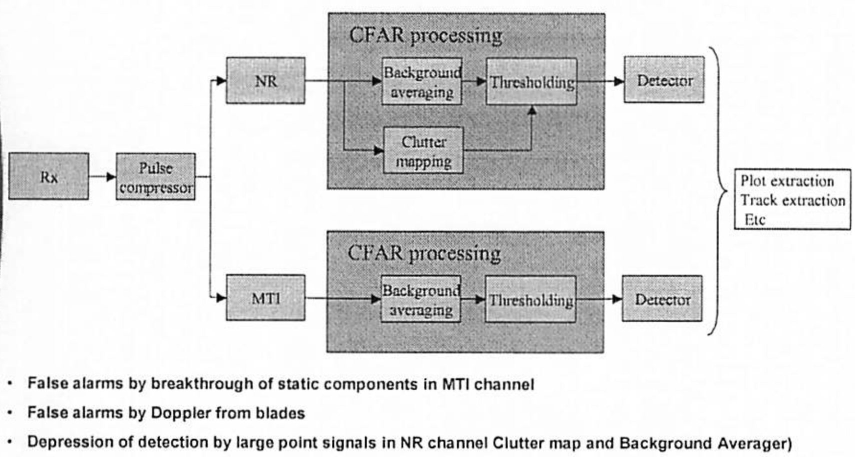
Nacelle

- Very large structure
- GRP housings are transparent to most radar frequencies
- Complex internal machinery difficult to model RCS
- Management of RCS – may be better to use reflective housing and shape/angle to minimise reflection direction

9

Generalised Signal Processing

This shows one of many different architectures for CFAR



- False alarms by breakthrough of static components in MTI channel
- False alarms by Doppler from blades
- Depression of detection by large point signals in NR channel Clutter map and Background Averager)
- Depression of detection by large point signals in MTI channel Background Averager
- Question – what RCS values will mitigate these effects?

10

Radar mechanisms

- Doppler processing channels designed to pass (e.g.) >30m/sec
- Adaptive Doppler processing usually designed for "mass velocity" of rain clouds, etc.
- CFAR affected by present of large "point" clutter, i.e., a single turbine
  - Background averager levels affected – cell censoring may be effective
  - Clutter maps affected, can have significant area effects on detection
- These symptoms are evident from trials, however -
- Scientific "cause and effect" chain is not yet proven

11

Use appropriate methods

- Mitigation measures are site-dependent
  - Holistic treatment of the wind farm/radar interaction
    - Wind farm toolbox
    - Avoid problems if possible
  - Best set of measures for any situation should be chosen
    - Identify the significant issues – false alarm rate, loss of detection......
    - Choose an appropriate solution
    - Robustness to varying wind farm parameters
- Today there is no "panacea" solution

12

The wind farm toolbox

- Tool 1 - Design the wind farm layout to be 'radar friendly':
  - turbine spacing, topology, turbine structure design, RCS management, etc
- Tool 2 – Adjust the radar settings to optimise performance
- Tool 3 – Modify the radars by:
  - Modify the radar processing design
  - Add extra filtering to the radar (ADT plot filter)
- Tool 4 - Screen the wind farm from the radar
- Tool 5 - Reinforce radar cover from another radar/sensor
  - Data fusion
- Tool 6 - Modify ATC procedures
- Tool 7 – Expertise to overcome residual problems

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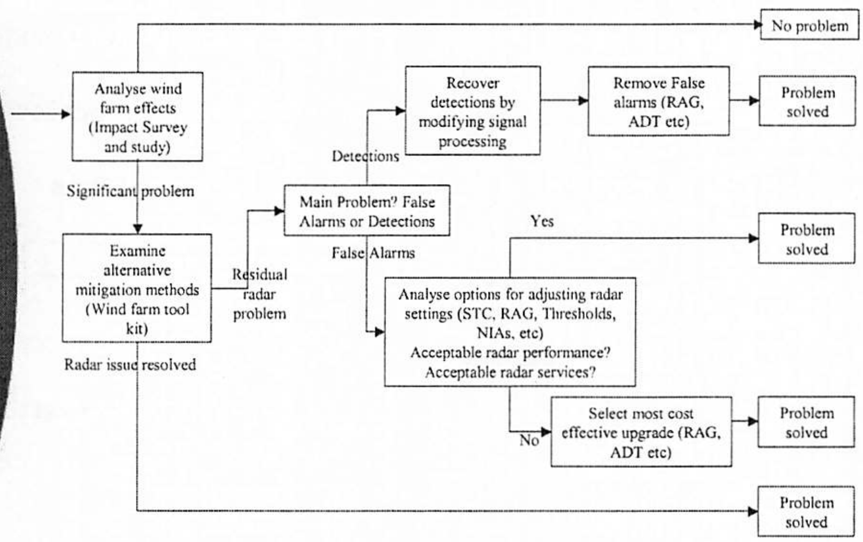
Radar mitigation decision tree – draft



Real life of more complex than this!

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The Advanced Digital Tracker

What is it?

- A post-processor that can be added to an existing radar installation

What does it do?

- Filters out unwanted plot from wind farms
- Enable radar sensitivity to be increased without increasing false plots and therefore work load on air traffic controllers or defence operators

How does it work?

- By associating detected plots with those detected on previous scans of the radar to determine which are from real aircraft
- By selecting which plots should be forwarded to the operators screens

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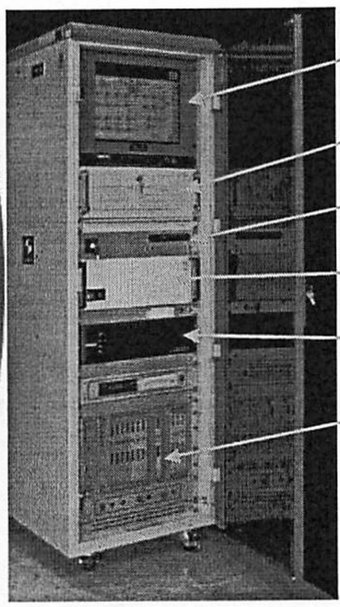
ADT hardware – typical installation



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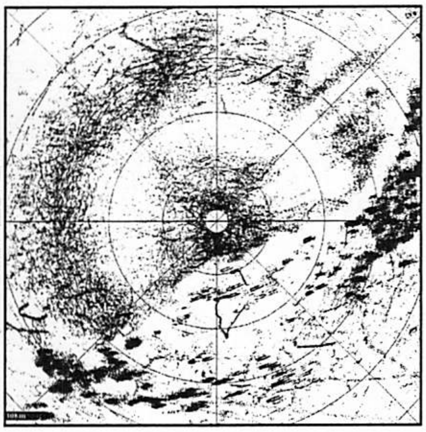
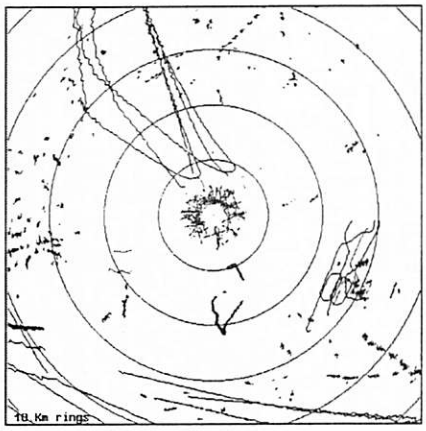
Example of Input & Output



Plot Input



Track Output

17

ADT Demonstration Programme

- Objectives:
  - Live demonstration of current ADT capabilities in representative wind farm conditions
  - Support further understanding of the science by extensive measurements
  - Support and demonstrate improved Plot-Filer algorithm
  - Give regulatory Authorities opportunities to understand the issues and the scope of improvements
- Programme
  - RAF providing mobile radar system (Tactical Watchman) and trials resources
  - Deploy to suitable location probably June this year
  - Combined funding DTI, AMS and consortium of wind farm developers

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AMS support to wind farms

- We are active in finding solutions that allow wind farms to coexist with radar
- Programmes demonstration to the regulatory authorities
- Supporting developers through "Impact Assessment Studies" to identify issues before submitting plans
- Active in developing better models and radar designs
- Contact:
  - Mr Geoff Butler
    AMS Ltd
    Cowes
    Isle of Wight
    07736811785

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Wind Radar Interference

Idaho National Laboratory

INL

Fact or Fiction?

Gary Seifert PE EE

March 2005

Wind Radar Interference, Fact or Fiction

- Overview
  - Interference
  - Who
  - When it Matters
  - The Process, Flawed or Working
  - What Can We Do
  - Next Steps

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Interference

- Is interference real, or an urban myth?
- What kind of interference?
- Considerations;
  - Interference is a relative term
  - In all cases of any new element in a zone monitored by radar, there is some new interference or impact
  - The real question is whether the impact affects the ability to get the job done
  - Less than 5% of installations worldwide impact the ability to do what needs to be done
  - However, placing a quantifiable value on that impact is difficult and often impossible

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Interference cont.

- Two main types of interference
  - Direct Interference
    - High reflectivity
    - Reducing sensitivity
    - False images
    - Shadowing areas
  - Doppler Interference
    - False targets
    - False MTI/MTD's
    - Impacts airborne radars

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Who is Impacted?

- Myth or reality?
- Experience shows that many claim impacts, most grievous and most believe them to be show stoppers
- Impacts come from two main communities
  - Military
  - Air traffic control
- But, are they real and significant?
  - A individual and personal value judgment
  - Personal history shows that 2-5% are real and significant
- In the end, it is always an individual issue driven by circumstance and specifics of the site

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Who is Impacted? Cont.

- Real impact examples
  - Training routes that are used for testing radar systems
  - Training routes that are used for training air crews on the use of radar systems
  - Installations close to facilities that have a need for discrimination of approaching traffic at low altitudes
    - Helicopter access zones
    - Attack corridors
    - Specialized radar and telemetry areas
  - Test and evaluation ranges

Common factor, specialized military mission impact areas

- Other
  - Approach and exit areas very close to airports entry and exit pathways

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Who is Impacted? Cont.

- Non-impact examples
  - Normal high altitude routes
  - ATC regions more than 15 miles from the Airports or transmitters
  - Distant wind farms served by radar systems with already developed filters (example Palm Springs, Boston, etc)
  - 95+% of wind farms in the USA

Bottom line, know the impact and address it individually

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When it Matters

- It matters when:
  - The wind farms take away national assets that can not be relocated or performed at other locations
  - The wind farms add unreasonable risk to national security
  - The benefits do not outweigh the impact
- However, Less than 5% of all proposed sites fit this category!
  - The real issue is to determine real impact, not perceived impact

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The Process, Flawed or Working?

- What is the process, or rather what should it be?
  - The normal process is to request permits and work through resolutions of impacts in all areas from environmental to radar.
  - Does it work?
  - Personal Observation – Only when both sides work together and want it to happen.
    - If either side wants to kill it, then success is limited
    - If military opposition is voiced at any level, projects often fail
    - But, how often are the concerns valid or mitigatable
    - How often are the comments and opposition based on a reluctance to change or address matters fairly
  - Getting a fair and impartial comment is nearly impossible the first time
  - Further, local authorities have no guidance on the power and authority in cases with conflicting input
- The question really becomes, what should the process be?

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What Can We Do?

- First and foremost – we all must be fair and reasonable in our approaches and expectations
  - A win-win solution is what is needed, but both sides of the issue want to be the winner
    - It is unreasonable for the developers to always get their permits
    - Just the same that it is unreasonable that the military can claim all sites to be significantly impacting and stop all installations
  - The best approach is to start early and identify concerns before final plans and permits are submitted.
  - Develop an understanding of the true concerns
  - Develop a respect for the existing issues from both sides
  - Remember that only a small percentage of sites can be denied and validated based on impact or mission

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What Can We Do? Cont.

- Develop a quantifiable impact statement
- Look at the impacts and develop workable proposals that address those impacts
- Develop open accountable communications
- Do not hide behind classification, it only impacts credibility
- Most issues can be addressed in an open forum to the level needed
- Work from the "What can we do" mode rather than from the "Why it can not be done" mode

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Next Steps

- Develop FAQ's that address the real issues generically
- Develop questions that developers can ask ATC and Military entities that will help develop an understanding of the real issues
- Develop Subject Matter Experts that can talk to both sides of the issues
- Ensure that the SME's are readily available to all communities
- Ensure that a portion of the SME's are cleared and can participate in controlled discussions
- Provide that support to the communities
- Help with general guidelines
  - Example – Turbines 100 miles from the nearest airport are not likely to impact performance of airport radar systems.
  - Examples – Turbines near secure facilities may not be compatible due to impact on surveillance radar systems
  - Most modern digital radar control systems have the ability to selectively blank out zones where radars are located with acceptable results as long as they are more than X-miles from the radar and do not create unacceptable shadow
  - And may more, etc.

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Next Steps Cont.

- Perform testing and validation of impacts and develop better guidelines based on verifiable and defendable information
- Train military personnel on real impacts and develop guidelines for their use
- Make sure that all organizations are consulted in military organizations
  - Example – Permits are usually addressed by facility and land use groups. But the impacted groups may be temporary tenants that have flight or test operations
- Develop universal guidelines so all agencies have consistent responses and processes
- Be good neighbors

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Can it work?

- Yes
  - It must be a fair and even process
  - Both sides of the system must be open and reasonable
  - Both "Yes and NO" are good answers depending on the individual circumstances

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Questions?

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Summary of IEA R&D Wind – 45th Topical Expert Meeting on

Radar, Radio, Radio Links and wind turbines

March 2005, London, UK

Mark Dorrington and Sven-Erik Thor

1 Background

Harnessing wind resources is important in tackling climate change with the development of the wind industry increasingly being viewed as a key renewable energy source, providing many benefits to new and existing markets. However, it is known that wind turbines or farms can have an adverse effect on the aviation domain. Therefore developments must take place in a way which takes full account of national air defence and air safety with both the wind energy and aviation communities understanding the needs of each other.

Essentially there are two ways in which the design of a wind turbine or wind farm may impact upon aviation operations:

- The physical obstruction caused by a tall structure; and
- The effects that rotating turbine blades can have on a variety of navigational aids and other equipment.

A major constraint on the deployment of wind energy is the restriction on siting turbines due to the potentially hazardous effects they may have on aviation and related defence interests. Objections have arisen over the potential effects on radar systems for both air traffic control and air defence and the impact on military low flying. The disturbance caused by wind turbines on various radar systems is not well understood and there is a lack of consensus on the severity of such effects. Nevertheless, major concerns have arisen within the aviation community regarding the potential for interference with radar systems and the subsequent effects on operations. However, the conflicting two interests seems to be much less significant in some European countries where extensive wind energy developments exist.

One country where steps are being taken to address any potential conflict is the UK, where the Department of Trade and Industry (DTI) has set up a 'Wind Energy, Defence and Civil Aviation Interests Working Group' to investigate the issues of concern and improve understanding within both the aviation and wind energy industries. In parallel with this study, other work has been commissioned; specifically, scientific studies to improve the understanding of the impact from wind turbines on radar systems; and the creation of guidelines aimed primarily, but not exclusively, at wind energy developers, outlining the interactions between wind farms and aviation[1].

The aviation community worldwide has procedures in place which are designed to assess the potential effect of developments such as wind farms on its activities and, where necessary, to identify mitigating measures. Both wind energy and aviation are important to Global interests. Furthermore, defence remains one of the prime responsibilities of any Government. All communities involved in wind energy and aviation have legitimate interests that must be balanced to identify a way ahead that gives the best results, taking into account each country's overall national context. Neither aviation nor the wind industry is static and developments can be expected in both domains that may change the effects they have on each other.

[1] 'Wind Energy and Aviation Interests – Interim Guidelines' (ETSU W/14/00626/REP), DTI, October 2002.

A study undertaken in 2002, entitled, 'Wind Turbines and Aviation Interests – European Experience and practice'[2] highlights the quite varying approaches and attitudes to wind power and how this has shaped policies, procedures and developments. The reasons include politics, geography, economics and history and have resulted in wind industries at varying stages of evolution. Broadly speaking, the conflict of interest between wind energy and aviation is less significant in some countries, albeit to varying degrees. For example, in Denmark the two seem to coexist most easily. In the Netherlands, also, aviation interests do not appear to impinge on wind energy developments. In Germany, friction has appeared in the past between the two interests and may well increase in the future, but this has not prevented the rapid growth of wind energy development. In Sweden there has been a similar amount of interest in the issue as in the UK, particularly with reference to the effects of turbines on technical systems. However, the tightest restrictions in Sweden come not from aviation specifically, but from other military activities unique to Sweden, such as radio links etc.

2 Presentations

A total of 27 participants attended this meeting with representatives from; Norway, Sweden, the Netherlands, UK and USA. A broad spectra of organisations were present encompassing government agencies, R&D establishments, private companies and developers.

Presentations were centered round the following topics:

- National policies, experience and regulations
- Radar interference and related issues
- Other topics including radio links and direction finding
- Mitigating technologies/preventive measures

Most presentations focused on the potential problems surrounding radar and navigational systems with supporting technical background. Measures to avoid these problems were described in presentations 6, 7 and 15.

These presentations conclude that mitigating technologies and computer software solutions such as radar filters and intelligent processing of multiple sensor data are available. These initiatives are being progressed with the aim of finding workable solutions to the radar problem that are acceptable to aviation regulators.

2.1 National policies experiences and regulations

The UK has been early in identifying the potential conflict between wind power and aviation with the establishment of a national Aviation Steering Group (2001), and the publication of a set of guidelines (2002). This initiative was undertaken by the Department of Industry and Trade (DTI) with the objective to produce public domain guidance on the appropriate siting of both onshore and offshore wind turbines, with respect to their likely effects on defence and civil aviation interests. Revised guidelines are currently being prepared with the intention to publish in October 2005. For more information see presentations 1-3, 5, 6 and 8.

Sweden took the first steps in this direction in 1995. Meetings were held with the Swedish government following the blocking of several wind power projects by the military. In some parts of Sweden the number of rejected projects, due to military interests, was high. Statistics from the period 1993 to 1998 reveal that 15% of the applications were turned down for military reasons. In response a number of studies were initiated to investigate the potential

---

[2] 'Wind Turbines and Aviation Interests – European Experience and Practice (ETSU W/14/00624/REP), DTI URN N°. 03/515, 2002.

conflicts between radar, radio links, direction finding systems, surveillance systems under the sea level and wind turbines. For more information see presentations 11-14.

Norway has recently started a project similar to the Swedish study. See presentation 9.

In the Netherlands the Royal Netherland Air Force initiated research in 1996, in response to plans for a large number of wind turbines in a northern Netherlands province. A research program was initiated including among others: the effect of shadowing by wind turbines, including algorithm development and measurements, various investigations involving air control radar. See presentation 4.

2.2 Radar interference and related issues

Many of the presentations highlighted that one of the major constraints on the deployment of wind energy is the restriction on siting turbines due to the potentially hazardous effects they may have on aviation and related defence interests. Objections have arisen over the potential effects on radar systems for both air traffic control, air defence and other navigational systems. In the UK it was reported that during 2004 approximately 50% of wind farm applications were rejected by the MoD, 66% of which resulted from concerns with radar interference.

The interference caused by wind turbines on various radar systems is not yet fully understood and there appears to be a lack of consensus throughout Europe as to the severity of such effects and how they should be calculated. Nevertheless, many studies are being progressed, particularly in the UK, which are leading to a better understanding as to how these issues can be mitigated.

Presentations 3, 4, 7 and 14 outlined the initiatives being progressed with the aim of finding a solution to the radar problem. These solutions employ software/computational methodologies to classify the interference.

One presentation (Aerotech Telub AB, Saab, Sweden), highlighted the different methods of approach (within Europe) when utilising models for pre-planning applications. The method adopted by Aerotech Telub was considered as being too severe in the way input data was interpreted. Thus leading to a high number of rejections for the wind developers.

In summary two possible methods to reduce radar interference were presented:

- Software technology (algorithm development) to optimise radar systems in mitigating radar/wind farm interactions
- Make wind turbine components less visible to radar signals, see 2.4 below

2.3 Radio links, direction finding etc

These topics were considered to be of less importance compared to radar effects. Studies have been performed in Sweden, the UK and studies are currently underway in Norway.

2.4 Preventive measures

Presentations 7 and 8 outlined two different methods for reducing Radar Cross Section (RCS) based on Radar Absorbing Material (RAM). One possible conclusion was that RCS-reducing hardware treatment may have the potential to facilitate the deployment of both onshore and offshore wind farms.

Vestas representative informed the meeting that they have plans to incorporate RCM reducing techniques as an option in some of their turbines, based on the QinetiQ system.

3 Summary of discussion

Following the two days of presentations the floor was opened and a general discussion took place. There was general agreement that the meeting highlighted the quite varying approaches and attitudes, throughout the IEA member countries, towards wind power and how this has shaped policies, procedures and developments. The meeting has inevitably provided the opportunity to identify possible future research needs and stimulate comments on the validity of existing models and evolving mitigating technologies with the potential for international collaboration to further increase knowledge and understanding.

In summary the following specific points were raised:

- Validity of the different physical models employed for evaluating radar influence currently lack consensus
- A clear understanding of the physics behind the reflectivity of turbine components must be established in order to develop a physical model which can be used by everyone
- For these models to be credible it is important that 'real life' data be incorporated - presentations reveal that several countries had not collected any 'real life' data
- Correlations between models and 'real life' situations have to be of an acceptable level (factor of 2)
- Simple model can be used by wind industry to assess potential problems, complex model can be used to resolve issues
- Recognised that release of input information for model is sometimes difficult due to classification issues
- The method adopted by Aerotech Telub was considered as being too severe in the way input data was interpreted
- It is important to develop software technology to optimise radar systems in mitigating radar/wind farm interactions
- Radar Absorbing Material offers an alternative solution but further development is needed to assess technical and financial feasibility
- Radar issues are the main source of conflict between the wind and aviation communities, whilst radio link and direction finding are of a lower priority.

At the end of the meeting there was a discussion on a possible future exchange of knowledge within this area. Most participants were in favour of this recommendation. Interest was expressed in establishing an annual IEA Joint Action Symposium. This proposal will be discussed at the forthcoming Executive Committee meeting in Portugal at the beginning of May. In addition the Department of Trade and Industry (DTI), UK offered to host a meeting in six months time so that developments on UK mitigating technologies and work undertaken by the MoD could be presented. Although this would not fall under the IEA's remit the DTI felt that it was important to update member countries on these important developments.

Possible items for future meetings are:

- Database of real observations
- Methods for technical analysis and computation
- Consensus about physical models
- Software "fixes"
- Stealth technologies

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IEA R&D Wind Annex XI, Topical Expert Meeting
RADAR, RADIO, RADIO LINKS AND WIND TURBINES
London 17 - 18 March, 2005

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