INTERNATIONAL ENERGY AGENCY

Implementing Agreement for Co-operation in the Research, Development and Deployment of Wind Turbine Systems
Task 11

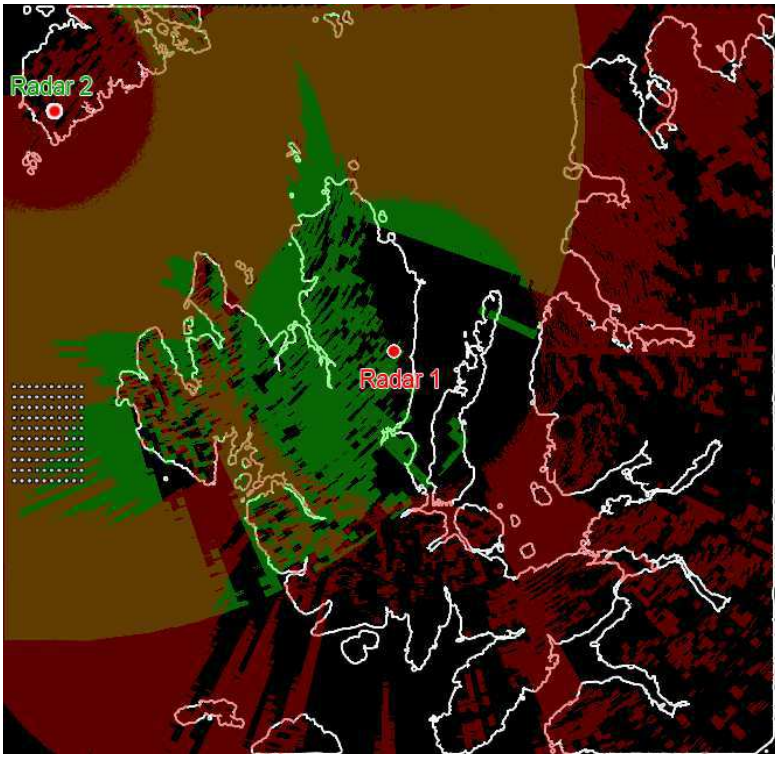
Topical Expert Meeting #83 on

MITIGATION OF WIND TURBINE IMPACTS ON RADAR

October 6th and 7th 2015

Fraunhofer FHR

53343 Wachtberg, Germany



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After one year the proceedings can be distributed to all countries, that is November 2016

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For more information about IEA Wind see www.ieawind.org

International Energy Agency

Implement Agreement for Co-operation in the Research, Development and Deployment of Wind Turbine Systems: IEA Wind

The IEA international collaboration on energy technology and RD&D is organized under the legal structure of Implementing Agreements, in which Governments, or their delegated agents, participate as Contracting Parties and undertake Tasks identified in specific Annexes.

The IEA's Wind Implementing Agreement began in 1977, and is now called the Implementing Agreement for Co-operation in the Research, Development, and Deployment of Wind Energy Systems (IEA Wind). At present, 24 contracting parties from 20 countries, the European Commission, and the European Wind Energy Association (EWEA) participate in IEA Wind. Austria, Canada, Denmark, the European Commission, EWEA, France, Finland, Germany, Greece, Ireland, Italy (two contracting parties), Japan, Republic of Korea, Mexico, Netherlands, Norway (two contracting parties), Portugal, Spain, Sweden, Switzerland, United Kingdom and the United States are now members.

The development and maturing of wind energy technology over the past 30 years has been facilitated through vigorous national programs of research, development, demonstration, and financial incentives. In this process, IEA Wind has played a role by providing a flexible framework for cost-effective joint research projects and information exchange.

The mission of the IEA Wind Agreement continues to be to encourage and support the technological development and global deployment of wind energy technology. To do this, the contracting parties exchange information on their continuing and planned activities and participate in IEA Wind Tasks regarding cooperative research, development, and demonstration of wind systems.

Task 11 of the IEA Wind Agreement, Base Technology Information Exchange, has the objective to promote and disseminate knowledge through cooperative activities and information exchange on R&D topics of common interest to the Task members. These cooperative activities have been part of the Wind Implementing Agreement since 1978.

Task 11 is an important instrument of IEA Wind. It can react flexibly on new technical and scientific developments and information needs. It brings the latest knowledge to wind energy players in the member countries and collects information and recommendations for the work of the IEA Wind Agreement. Task 11 is also an important catalyst for starting new tasks within IEA Wind.

IEA Wind TASK 11: BASE TECHNOLOGY INFORMATION EXCHANGE

The objective of this Task is to promote disseminating knowledge through cooperative activities and information exchange on R&D topics of common interest. Four meetings on different topics are arranged every year, gathering active researchers and experts. These cooperative activities have been part of the Agreement since 1978.

Carballeira Wind Farm - Spain

Two Subtasks

The task includes two subtasks.

The objective of the first subtask is to develop recommended practices (RP). In 2013 were edited RPs on "Social Acceptance of Wind Energy Projects", "Wind Integration Studies" and. "Ground-Based Vertically Profiling Remote Sensing for Wind Resource Assessment".

The objective of the second subtask is to conduct topical expert meetings in research areas identified by the IEA R&D Wind Executive Committee. The Executive Committee designates topics in research areas of current interest, which requires an exchange of information. So far, Topical Expert Meetings are arranged four times a year.

Documentation

Since these activities were initiated in 1978, more than 70 volumes of proceedings have been published. In the series of Recommended Practices 16 documents were published and five of these have revised editions.

All documents produced under Task 11 and published by the Operating Agent are available to citizens of member countries participating in this Task.

Operating Agent

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COUNTRIES PRESENTLY PARTICIPATING IN THE TASK 11	
COUNTRY	**INSTITUTION**
Denmark	Danish Technical University (DTU) - Risø National Laboratory
Republic of China	Chinese Wind Energy Association (CWEA)
Finland	Technical Research Centre of Finland - VTT Energy
Germany	Bundesministerium für Umwelt , Naturschutz und Reaktorsicherheit -BMU
Ireland	Sustainable Energy Ireland - SEI
Italy	Ricerca sul sistema energetico, (RSE S.p.A.)
Japan	National Institute of Advanced Industrial Science and Technology AIST
Mexico	Instituto de Investigaciones Electricas - IEE
Netherlands	Rijksdient voor Ondernemend Nederland (RVO)
Norway	The Norwegian Water Resources and Energy Directorate - NVE
Spain	Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas CIEMAT
Sweden	Energimyndigheten – Swedish Energy Agency
Switzerland	Swiss Federal Office of Energy - SFOE
United Kingdom	CATAPULT Offshore Renewable Energy
United States	The U.S Department of Energy -DOE

CONTENTS

PRESENTATIONS

1. INTRODUCTORY NOTE

The development of wind farms onshore and offshore, as a rational and sustainable source of renewable energy, interferes with radar surveillance and radio communications. Wind turbines produce shadow in radar beams, the moving blades cause reflections and the intermittent clutter can create false tracks, obscure or seduce real targets. The rotating blades defeat traditional Moving Target Indicator processing.

Three IEA Wind Topical Expert Meetings on the Topic "Radar, Radio Links and Wind Turbines" were organized in the past:

- TEM#60 in November 2009. (SenterNovem – Netherlands).
- TEM#53 in March 2007 (Oxford, UK)
- TEM#45 on March 2005 (London, UK)

Summaries of these meetings could be download from the IEA Wind web site:

- http://www.ieawind.org/Task_11/TopicalExpert/Summary_60.pdf
- http://www.ieawind.org/Task_11/TopicalExpert/Summary_53.pdf
- http://www.ieawind.org/Task_11/TopicalExpert/Summary_45_Radar.pdf

Also the full proceedings of the TEM#60 meeting could be download from the IEA Wind web site:

- http://www.ieawind.org/Task_11/TopicalExpert/60_Radar%20Radio%20and%20Wind%20Turbines%202.pdf

At the previous IEA R&D Topical Expert Meetings on the subject "Radar, Radio and Wind turbines" the effects of wind turbines on radar and radio systems have been presented from the perspective of wind farm and radar system operators. Mitigating techniques and ways to work around the policy issues have been discussed.

The objective of this new meeting is to exchange information from experts who are working with mechanisms, tools, or equipment which can help mitigate the problem wind turbines cause for radars. Topics for discussion may include:

- Radar friendly wind turbine blades
- Lower RCS (Radar Cross Section)
- Lightning mitigation systems for wind turbines,
- New/modified/infill radars
- Radar processing improvements
- Wind turbine-radar test activities.

This TEM will help develop and understanding of where we are with respect to mitigating the effect of wind turbines on radars, and will offer potential mechanisms to mitigate this barrier to wind turbine deployment in areas near long range air defense, air traffic control and weather radars. The technical experts will also identify knowledge gaps and topics for which further collaboration and research are needed.

1.1 Recent developments

Without being exhaustive several developments show that the challenges of enabling radar surveillance to coexist with wind energy development are on the brink of being found.

The radar industry is actively developing mitigation strategies to counter the negative effects of Wind Farms upon radar coverage. BAE Systems, Raytheon, Thales and others all work hard on new techniques for enabling continued aircraft detection within wind turbine clutter. But also knowledge institutions develop new insights which are of increasing interest to the radar and wind turbine communities.

Within NATO dedicated SET group meetings on the subject were organised between air traffic controllers and radar industry.

In responses to increasing reports of interference between surveillance sensors and wind turbines, the EUROCONTROL Surveillance Team established a Wind Turbine Task Force. EUROCONTROL is the European Organisation for the Safety of Air Navigation that has 38 Member States from across Europe.

EUROCONTROL has issued “Guidelines on How to Assess the Potential Impact of Wind Turbines on Surveillance Sensors” for consultation. The Guidelines consider the impact of wind turbines on both primary surveillance radar (PSR) and secondary surveillance radar (SSR).

The draft Guidelines are described as a reference guide for radar operators and wind energy developers and contain a methodology recommended by EUROCONTROL. It is the intention that they will become part of an international safeguarding document.

There are other documents and guidelines relating to wind farms and radar issued by ANSPs, national regulators, national governments, ICAO and NATO. Some ANSPs, regulators and governments have little formal guidance on wind farms and radar. As these bodies see the need for guidance they will develop new guidelines or adopt existing ones.

The Guidelines influence may increase over time for a number of reasons. Awareness of the wind farm radar issue and the Guidelines will increase as more wind farms are built. New national guidelines are likely to be derived from the European guidelines. National aviation functions will gradually be replaced by European ones and non- EUROCONTROL states will be influenced by the Guidelines.

1.2 Expected Outcome

The goal of the meeting is to gather knowledge on recent developments to make maximum growth of wind energy possible whilst maintaining an acceptable level of safety and security. By gathering and exchanging information we hope to achieve a common understanding of issues.

These issues are the way that wind turbines interfere with radar systems and the developments to handle it, how to work around, changing standards, hardware or software of radar systems or via mitigation and developments of wind turbines and farms.

2. AGENDA

AGENDA

IEA Wind Topical Expert Meeting #83 *on*

MITIGATION OF WIND TURBINE IMPACTS ON RADAR

October 6th and 7th 2015

Fraunhofer FHR

53343 Wachtberg, Germany
Phone: +49 9435-557
Fax: +49 9435-627
Internet: www.fhr.fraunhofer.de

Tuesday 6th October

>09:00 **Registration**. Collection of presentations

>09:30 **Introduction by Host**
Dr. Heiner Kuschel, Fraunhofer Institute FHR

>09: 50 **Recognition of Participants**

>10:00 **Introduction by Task 11 Operating Agent.**
Dr.Xabier Munduate, CENER

>10:30 **Introduction to TEM**
Dr. Heiner Kuschel, Fraunhofer Institute FHR

●10:30 Coffee Break

1st Session Individual Presentations (11:00-13:00)

>11:00 **Weather radars & wind turbines: impact and mitigation**

Mr. Lars Norin, Swedish Meteorological and Hydrological Institute, Sweden

>11:30 **Impact of wind turbines on military radars**
Joseph Warms, Fraunhofer Institute FHR, Germany

>12:00 **IFT&E Summary and Wind – Radar Interference Mitigation R&D**

Jason Biddle, MIT Lincoln Laboratory, USA

>12:30 **PERSEUS modeling, the step towards regulation within The Netherlands**

Dr. Onno Van Gent, TNO, The Netherlands

●13:00 Lunch

2nd Session Individual Presentations (14:30-16:00)

>14:30 **The importance of site specific wind farm modelling in radar impact assessments**
Dr. Tony Brown, University of Manchester, UK

>15:00 **PARASOL, collision avoidance illumination on demand**

Dr. Heiner Kuschel and Dr. Christoph Wasserzier, Fraunhofer Institute FHR, Germany

●16:00 Coffee Break

3rd Session Individual Presentations (16:30-17:30)

>16:30 **Mastery of radar signatures of wind turbine and their impact on radar**

Dr Jean Paul Marcelin, ONERA, France

●17:00 End of the Tuesday meeting

Wednesday 7th October

4th Session Individual Presentations (9:00-10:30)

>09:00 **Proven and Promising Mitigation strategic**
Kai Frolic, Pager Power, UK

>09:30 **Radar vs Wind Power. Radar, radio and wind turbines**
Eldar Aarholt, Teleplan AS, Norway

●10:00 Coffee Break

Final Discussion (10:15-11:15)

>10:15 **Discussion**

>11:00 **Summary of Meeting**

>11:15 **End of the meeting**

Technical Visit to the FHR Space observation radar TIRA.

3. LIST OF PARTICIPANTS

The meeting was attended by 16 participants (intended 19) from 8 countries. Table 1 lists the participants and their affiliations.

	Name	Surname	Company	Country
1	Lars	Norin	Swedish Meteorological and Hydrologic	Sweden
2	Heiner	Kuschel	Fraunhofer Institute FHR	Germany
3	Christoph	Wasserzier	Fraunhofer Institute FHR	Germany
4	Josef G	Worms	Fraunhofer Institute FHR	Germany
5	Martin	Maslaton	MASLATON Rechtsanwaltsgesellschaft r	Germany
6	JCB	BIDDLE	MIT LINCOLN LABORATORY	USA
7	Hilde	Aass	Norwegian Water Resources and Energy	Norway
8	~~Ben~~	~~Miller~~	~~SANDIA NATIONAL LABORATORIES~~	~~USA~~
9	~~William~~	~~Van Houten~~	~~DOD Siting Clearinghouse~~	~~USA~~
10	Eldar	Aarholt	Teleplan AS	Norway
11	AK	Brown	University of Manchester	UK
12	~~Nicola~~	~~Vaughan~~	~~OSPREY CONSULTING SERVICES~~	~~UK~~
13	Patrick	Gilman	US DEPARTMENT OF ENERGY	USA
14	Onno	Van Gent	TNO	NL
15	Jean Paul	Marcelin	ONERA	France
16	Kai	Frolic	Pager Power	UK
17	Reinier	Tan	TNO	NL
18	Rolf	Andorfer	MoD	Germany
19	Xabier	Munduate	CENER	Spain

4. SUMMARY

Here are presented the minutes of the IEA Wind Topical Expert Meeting TEM 83 on Mitigation of Wind Turbine Impact on Radars together with a summary of the more relevant aspects that were exposed by the participants.

Multidisciplinary backgrounds converged at the meeting. Aviation authority, Expertise on wave propagation, radars (Meteo and Aviation), and magnetic fields signals from wind farms. Experts on wind turbine interference, that have been coordinating wind turbine assessments and are interested on primary and secondary radars to diminish the impact of wind turbines. Consultants that have been working on real solutions for Eurocontrol and the British offshore wind farms and assisted to the previous TEMs on radar 2005, 2007 and 2009. Some experts with 30 years' experience with radars, and 10 years modelling wind farms in offshore. Impressive and real projects and solutions from the USA side where shared.

1.- Lars Norin. Sweedish Meteo and Hydro Institute

His focus is on Weather systems where his interest is to follow rain in real time and hydrological issues. They do not have a problem with wind turbines in a single snapshot but they do on averaged data, resulting in a reduction in precipitation. Increasing receptivity the signal is fine. Once, the SWERAD Military and the Meteo office had a problem and the proposed solution was a Gap Filling Radar.

2.- Joseph Warms FHR. Wind Turbines impact on Military Radars

He presented electromagnetic calculations and validations of radar measurements in static and in a small aircraft. He studies the propagation paths. They use 500 MHz measurements or more to get radar measurements in real time. He detected something new: Observed Fluctuations of pulse power over time. There are some windfarms that present these fluctuations and others don't. This may be interesting.

3.- Jason C. Lincoln Laboratory MIT. Summary of Wind and Radar

He presented results from IFT &E project that finished in 2013. He mentioned that the area of impact on radar can be done as small as possible, but not to totally disappear. There are solutions that can be implemented on blade design, on wind farm design and on radar replacement.

4.- Onno Van Gent. TNO. PERSEUS modeling, the step towards regulation within The Netherlands.

They already have a study of the radar shadow from one wind turbine. But now with a wind farm they took the subject again. Since 1995 they have studied wind turbine radar interaction. They are assessing the whole country wind farms. They support the idea of putting secondary radars. They have a MSSR Tooling validated for a single obstacle. The worst case for the simulation accuracy is a single turbine. A wind farm is better simulated. He comments that the radar people in NL are quite open to discuss now.

5.- Tony Brown, The importance of site specific wind farm modelling

He started his work with electromagnetics and for the last 10 years the focus of his work is on offshore turbines and radar. He explains how the simple coast, single pulse is the radar for maritime ships. Old radars see the tower as a Doppler effect, although it does not move. The new radars do not have this problem. For ships, if they don't have a Doppler radar type, the wind turbines tower makes reflections and bounces, and this is important for the ship. For the aircrafts only the rotors have importance. In order to get a solution, absorbing materials were investigated but were difficult to conform and were too heavy. He concludes that high resolution Doppler is always a solution.

6.- Bryan Miller Sandia NL reduced Wind Turbine Signals

His experience is on how to reduce signal from turbines and the impact from wind farm siting. In Oregon (USA) in 2008 there was a problem in a windfarm, and since then they are working on that. They develop RCS materials at Sband of 2-4 GHz, they could reduce up to 20 dB put it into the spar cup. They have a licensed software (TSPEAR), a tool for developers to study the impact of wind farm siting on radars.

7.- Heiner Kuschel PARASOL

He explained the detection of aircrafts in the keep-out area of wind farms (4.5 km) with passive radar sensors distributed in the wind farm. The size is about 1.50 m mounted at 50 m to avoid blade interference. They have developed a system to avoid blade interference. Passive radar can fill gaps and can be used as health condition monitoring by micro Doppler analysis. He can use multiple transmitters, he knows the source, and he needs only to work the signal independently.

8.- Jean Paul Marcellin, ONERA

The French government asked Onera to investigate because Meteo France had some problems with wind turbines. In France if there is a potential problem with radars and wind farms, the problem is only considered under the opinion of radar operators. As a consequence more than 4GW are blocked in France because the decision to get the permission for wind farms depends only on the radar operators. He showed a 2D radar image, where the more critical areas are near the root of the blade, and the tip is less critical. This is in contrast to what Eldar Aarholt from Teleplan Consulting AS, Norway says, that the worse is the at the tip of the blade and not at the root.

9.- Kai Frolic. Pager Power UK. Proven and Promising Mitigation strategic

He presents a very interesting background on radar issues. In some countries the risk of any potential disturbances on the radar, falls on the radar operator. There are countries like South Africa, where the wind farm developers should assume the responsibility. He concludes that it is difficult to prove that the radar has been influenced by the wind turbine.

10.- Eldar Aarholt. Teleplan Consulting AS

The problem of radar interference by wind turbines happened 15 years ago and now it is resolved. In the year 2003 they were starting some problems with radars in Norway, wind farms were very close to the military site. He has been working closely with developers and military agents. Nowadays, modern radar has very few problems coping with wind farms.

In Norway military ask for 10 km distance from the wind farm to the radar, and usually is admitted by developers. The real problem is that sometimes it takes 8 years to get the wind farm permission. From 2008 most wind farms license applications were approved in Norway. Military accept some kind of disturbance and money if a real problem happens.

Blocking, Shadowing, Reflected signal and Multipath reflections is not a problem anymore. Only the case of a big wind farm cluster may be a problem for 2D radars. The problem of wind turbines on radar was resolved with education and information mostly.

From Norway Teleplan AS, Eldar Aarholt has work as consultant for Eurocontrol and the British offshore wind farms. Before that he worked on the military industry. He assisted to the previous TEMs on radar 2005, 2007 and 2009. In his opinion most of the issues are already saved related to the impact of wind turbines on radars

The discussion on mitigation of wind turbine impact on radar focussed on important issues:

1- The need for test sites: it will be interesting to see real time experiments, in particular Meteo moving rotor radars.

2- The answer to what is the best solution ready to apply now was:

Mitigation by reorientation of wind turbines, automatic switched selective signal, Wind Farm configuration, Radar configuration, and the cheap radar prizes compare to some years ago.

3- Related to how to tackle wind turbines configuration that are situated in a line:

They agree that multipath reflections is not a problem from wind farms where the wind turbines are in a line, and that only clutter – cluster configurations may be a problem for 2D radars, where a wall it is seem for the radar.

There was not 100% quorum, but the majority of the participants explained that the issue of wind turbine radars is very mature and satisfactory. They are approaches and engineering solutions to avoid any conflict and technical problem. Even where today technical solutions may reach the limit, governmental inclusion is a must to resolve the marginal problems. As an example the MOD Aviation specification in the UK, they have regulated that it can be "A volume where the radar does not read".

PRESENTATIONS

IEA TEM83, October 6th and 7th 2015 at Fraunhofer FHR

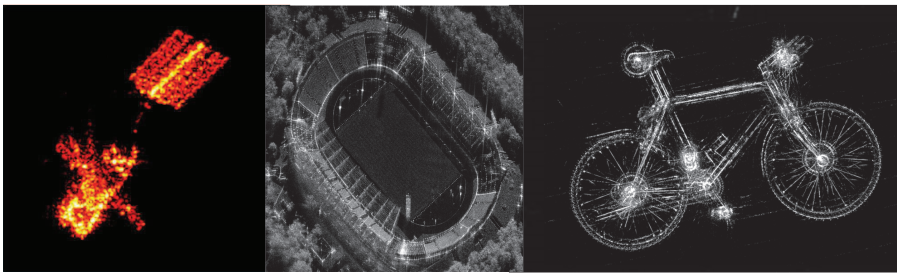
Welcome to Fraunhofer FHR

Dipl. Ing. Heiner Kuschel

Fraunhofer FHR

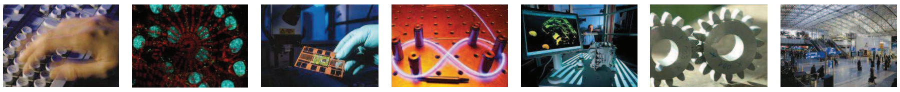
FRAUNHOFER-INSTITUT FÜR HOCHFREQUENZPHYSIK UND RADARTECHNIK FHR

Prof. Dr.-Ing. Joachim Ender
Head of Fraunhofer-Institut für Hochfrequenzphysik und Radartechnik FHR
Chair at Univ. Siegen, Center for Sensor Systems ZESS



Fraunhofer FHR

THE PROFILE OF THE FRAUNHOFER-GESELLSCHAFT



- 66 institutes and independent research units
- more than 22,000 staff

7 Groups:
- Information and Communication Technology
- Life Sciences
- **Microelectronics**
- Light & Surfaces
- Production
- Materials and Components – MATERIALS
- **Defense and Security**

The Fraunhofer-Gesellschaft undertakes applied research of direct utility to private and public enterprise and of wide benefit to society.

Fraunhofer FHR

FHR: Radar research since1957

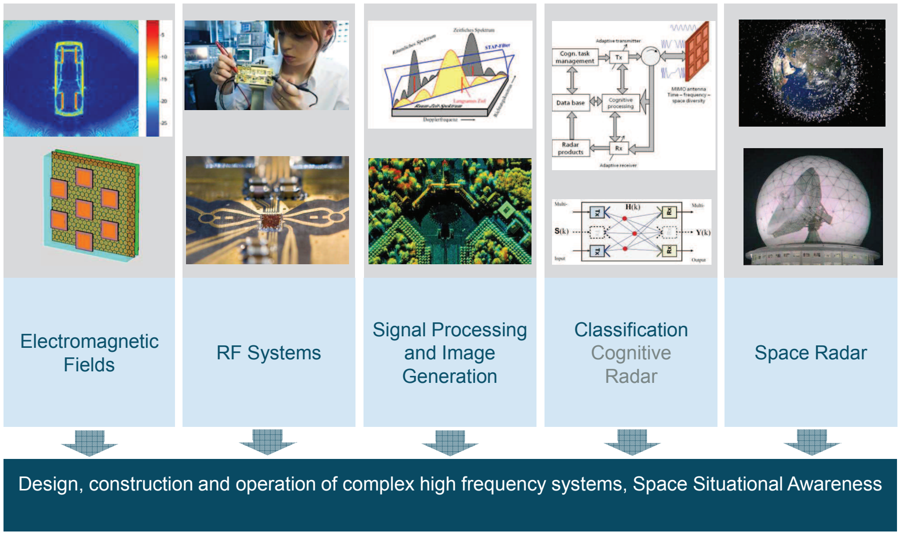
267 Employees, 22 Mio € Budget

Fraunhofer-Anwendungszentrum für multimodale und luftgestützte Sensorik (AMLS)
Rhein-Ahr-Campus Remagen

Fraunhofer FHR

Fraunhofer FHR

FHR: CORE COMPETENCES, INTERDISCIPLINARY COOPERATION



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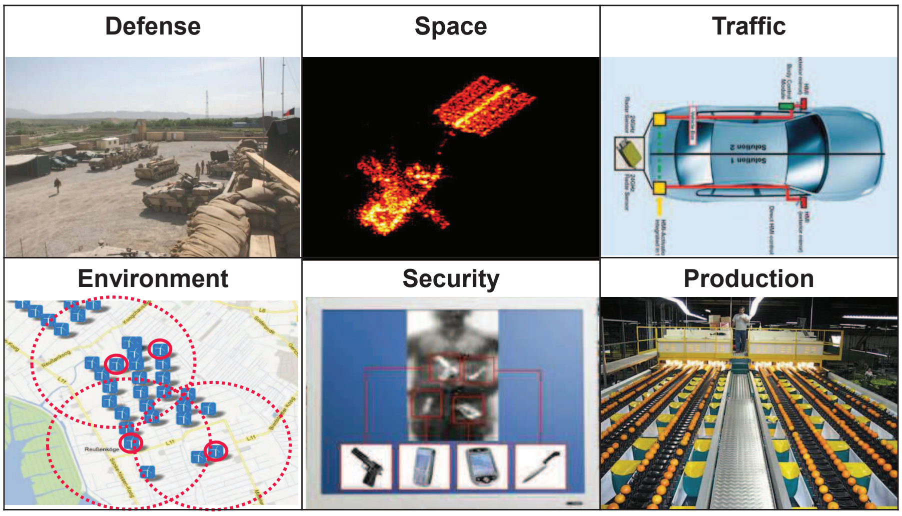
BUSINESS SEGMENTS FHR



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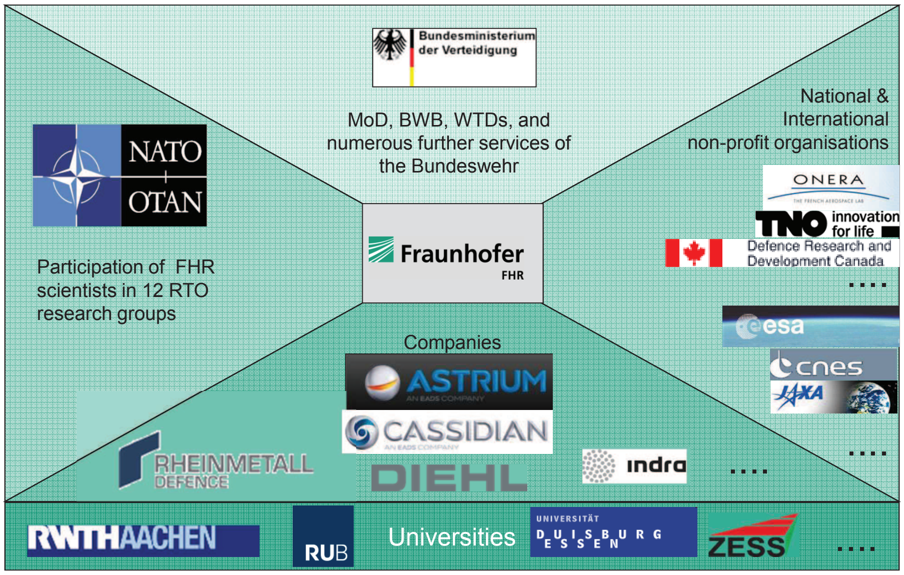
THE FHR NETWORK

Our partners



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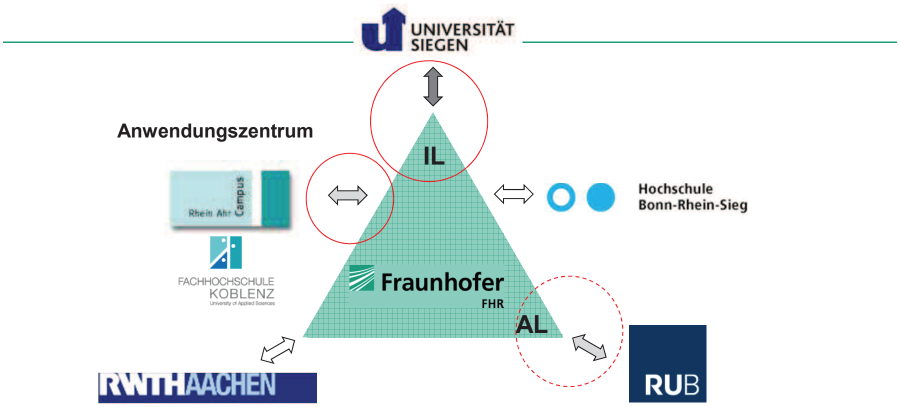
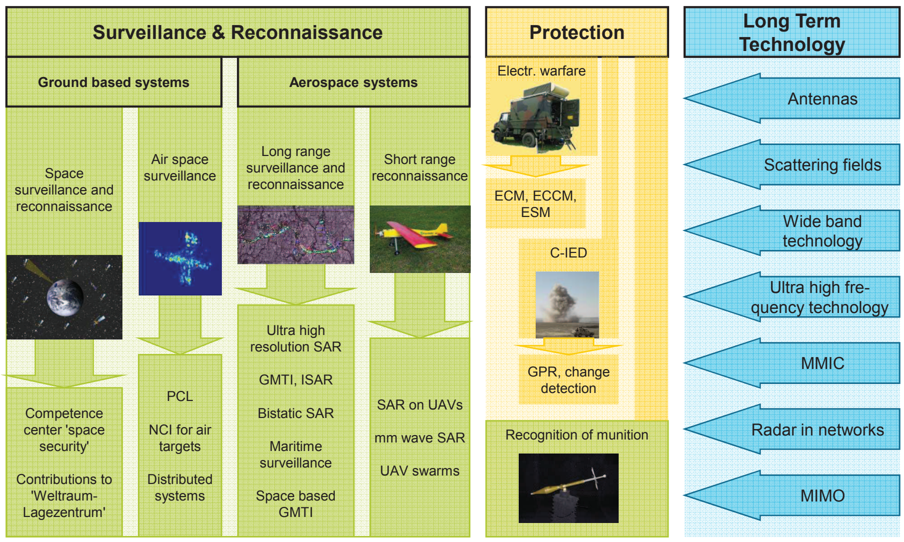
NETWORKS WITH UNIVERSITIES

- Science axis in southern NRW in the area electrical engineering



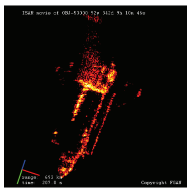
DEFENSE RESEARCH AT FHR - OVERVIEW



FHR CONTRIBUTES TO SECURITY IN SPACE

FHR – Competence Center Space Security

- **Knowledge base**
  - Physics of space and orbits
  - Actual situation of near Earth space
  - Overview on active and passive satellites in orbit
  - Space debris population
- Algorithms for high precise orbit determination and propagation
- ISAR imaging of space objects
- Techniques for de-orbiting prognostics
- Measurement and analysis of space debris

TIRA space observation radar

JAXA cnes esa KARI National Aeronautics and Space Administration DLR

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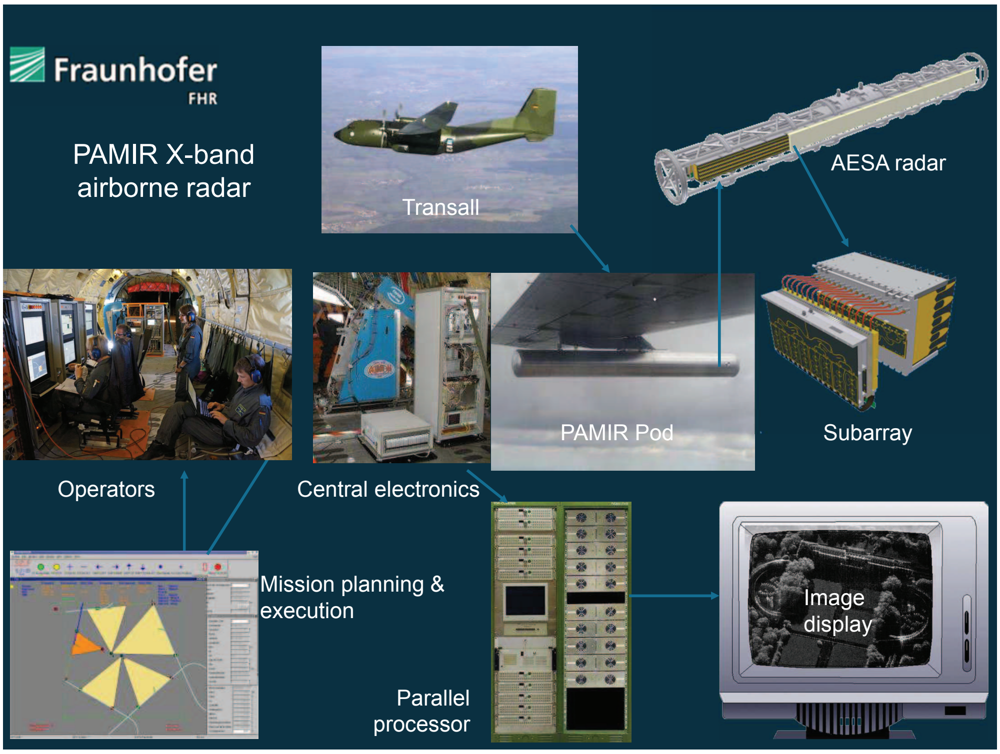
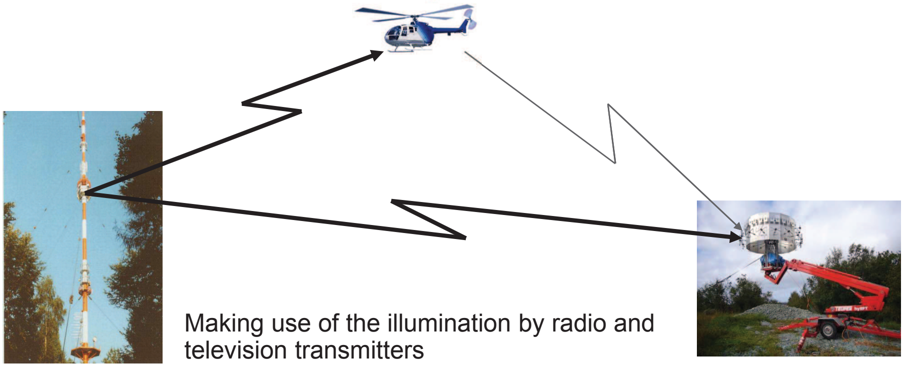
FHR
Our research
HIGH RESOLUTION SAR IMAGING
AND MOVING TARGET RECOGNITION


Fraunhofer
FHR
PAMIR X-band airborne radar
Transall
AESA radar
Subarray
PAMIR Pod
Operators
Central electronics
Mission planning & execution
Parallel processor
Image display

AIR SPACE SURVEILLANCE WITH PASSIVE RADAR

Passive coherent location (PCL)



Making use of the illumination by radio and television transmitters

- Observation of the lower airspace
- Recognition of low flying small aircraft

Fraunhofer FHR

SYSTEMS FOR SECURITY

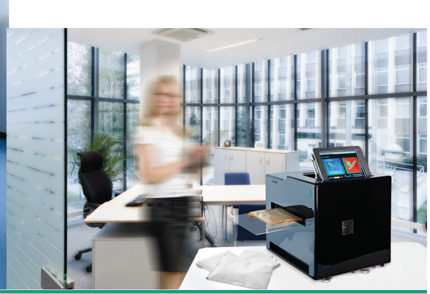
Person scanner, object scanner

SAR-Gate

- FHR person scanner for dynamic situations

SAMMI

- Stand-alone device for scanning of objects (e.g. letters)

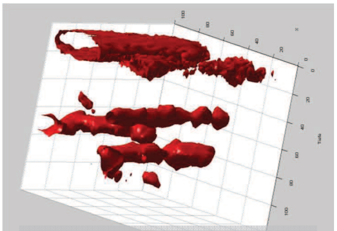


Fraunhofer FHR

ENVIRONMENT AND SAFETY
GROUND PENETRATING RADAR

- GPR:
  - Wide band wave forms from some tens of MHz to some GHz
  - High-resolution range profiles
  - Three-dimensional sub-surface imaging by use of synthetic apertures.
- Applications
  - Detection of buried land mines
  - Location of sub-surface installations
  - Detection of cavities
- Project: Prevention of accidents of building machines by recognition of cavities in the earth

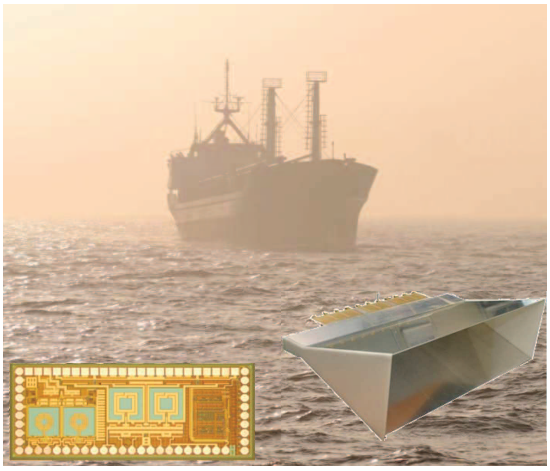
ZESS Universität Siegen — Fraunhofer FHR — Universität Stuttgart



Subsurface imaging (FHR)

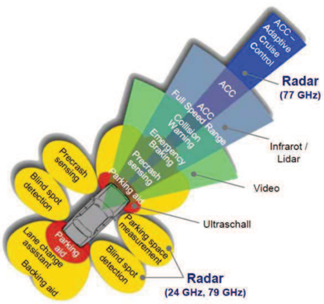
Fraunhofer FHR

TRAFFIC



- Magnetron-free radar for civilian shipping

- Antenna-Frontend for car assistance systems



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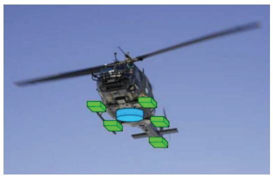
DEVELOPMENT OF A MILLIMETER-WAVE PILOT ASSISTANCE SYSTEM

Brownout/whiteout is a dangerous risk for landing helicopters



FHR develops a millimeter-wave radar system for safe landing at bad weather conditions.

The system will be integrated in the helicopters of the Bundeswehr.

Short technical tour to TIRA on Wednesday proposed

Coffee Breaks at 10:30h and 16:00h

Lunch im Cantina at 13:00h

Visit to TIRA on Wednesday 13:30h ?

Tuesday 19:00 Dinner at
Restaurant Blumenhof
Bahnhofstraße 1, 53340 Meckenheim

Weather radars & wind turbines: impact and mitigation

Lars Norin

SMHI
Research Department
Atmospheric Remote Sensing
Swedish Meteorological and Hydrological Institute

2015-10-06

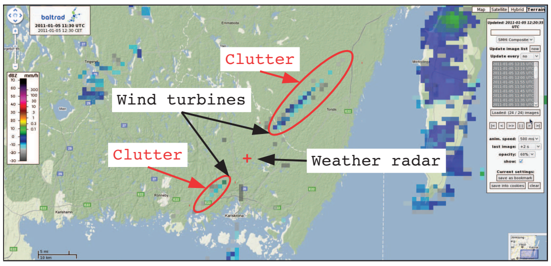
Outline

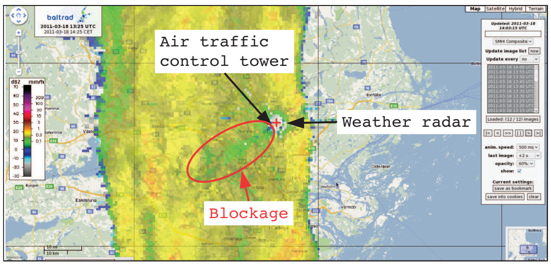
Background: Swedish weather radars

- 12 C-band Doppler radars, providing national coverage (about to be upgraded).
- Operate 24/7, scan 360° using various tilt angles.
- Preciptation measurements are used by meteorologists to follow weather in real time.
- Radar data are used by numerical weather prediction models.
- Radar data are used to drive hydrological models.

Background: Wind turbine impact — examples

- Wind turbines in weather radar line of sight disturb the radar and may cause erroneous measurements.
- Reflections off wind turbine blades give rise to clutter → overestimation of precipitation.
- Blockage leads to a reduction in echo strength → underestimation of precipitation.





Background: International recommendations

Range	Guideline
0–5 km	Wind turbines should not be installed in this zone.
5–20 km	Re-orientation or re-siting of individual turbines may reduce or mitigate the impact.
20–45 km	Notification is recommended.
$>$ 45 km	Notification is recommended.

WMO guidance statement on weather radar/wind turbine siting (2010).

Range	Statement
0–5 km	No wind turbine should be deployed within this range
5–20 km	Wind farm projects should be submitted for an impact study

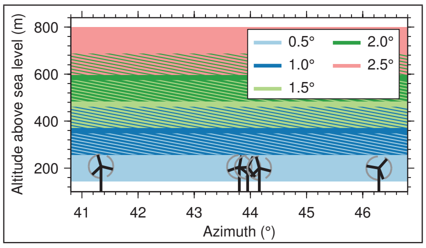
Statement of OPERA on C-band weather radar/wind turbine siting (2010).

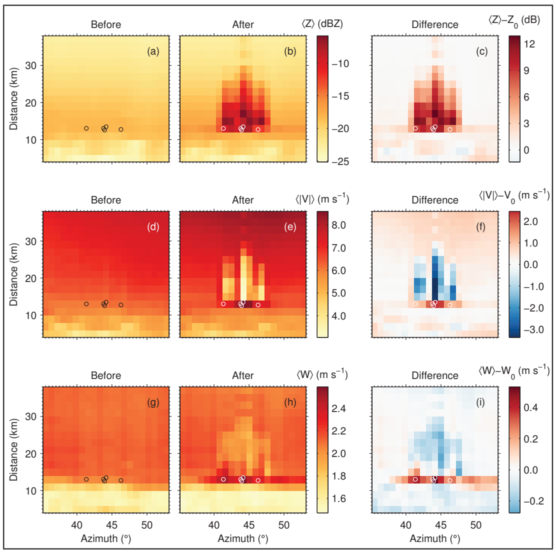
Background: Weather radars & wind turbines in Sweden

- Swedish weather radars owned by the Swedish Armed Forces (SAF) and SMHI.
- Weather radars are of military interest in Sweden.
- SAF have strong legal support to reject wind turbine applications.
- Applications were assessed manually $\rightarrow$ a prediction tool needed.

Observations: Detailed investigation

Lowest scan: 0.5°





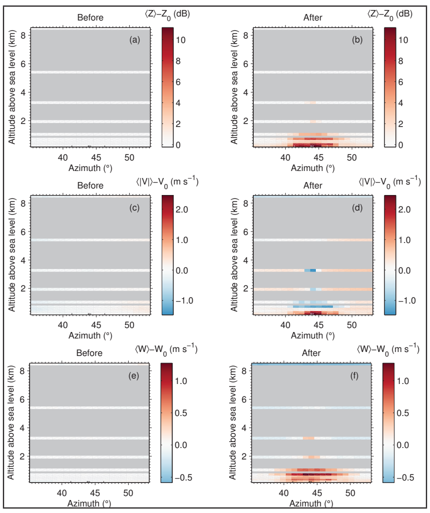
- Impact from five 150 m high wind turbines, 13 km from the radar.
- 6 years' worth of operational data analysed.
- Impact clearly seen on all three radar moments.

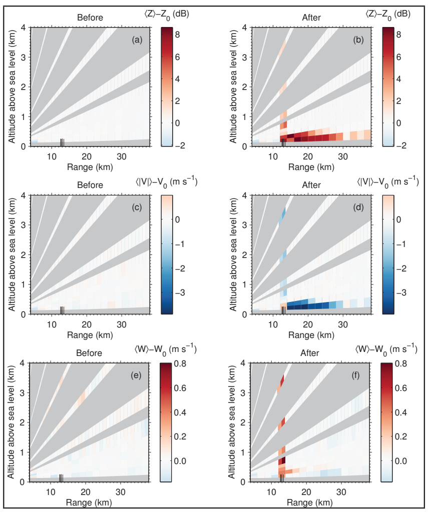
from Norin, Atmos. Meas. Tech., 2015

Observations: Vertical cuts

Distance = 13 km

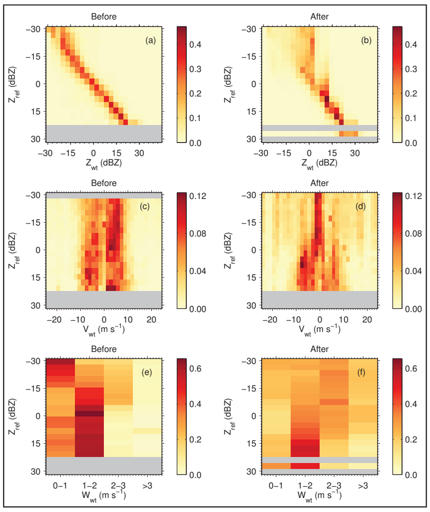
Azimuth = 44°



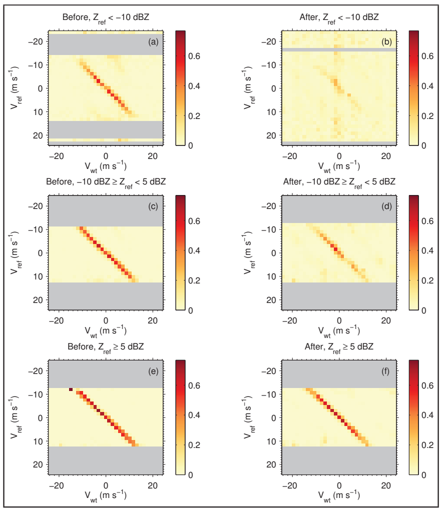


Observations: Recovery of the weather signal

All moments



Radial velocity

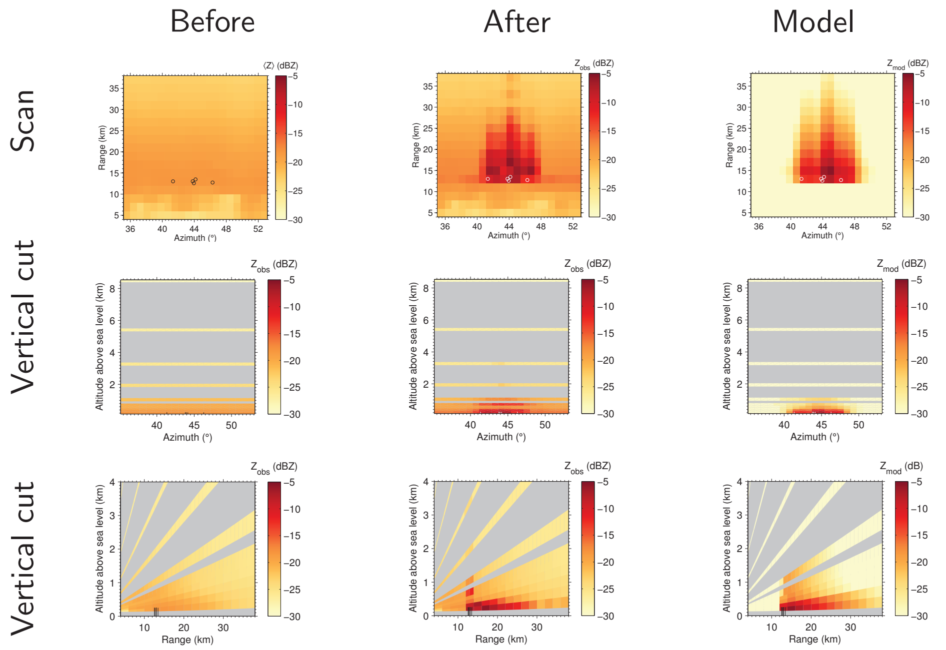


Conclusion: Modelling clutter (and blockage) is sufficient

Observations: Prediction tool

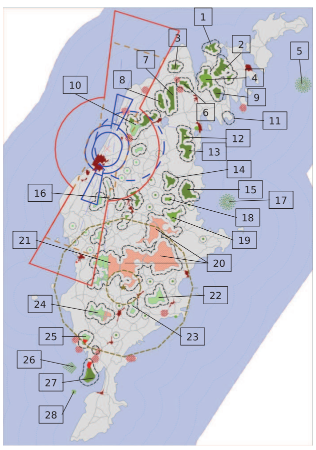
- Since 2011 the SAF uses the prediction tool, developed by the SMHI, to support their decisions.
- Predicts clutter and blockage.
- The model simulates the radars' measurement protocols.
- Takes existing wind turbines into account.

Observations: Model



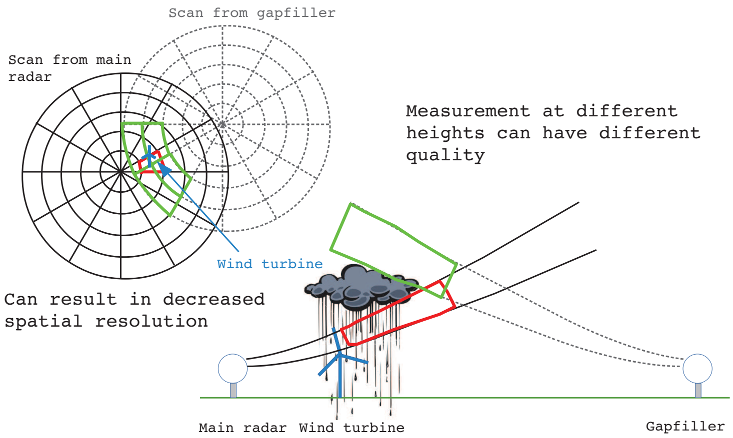
Mitigation: Background

- On the island Gotland in the Baltic Sea wind conditions are favourable for wind turbines.
- A weather radar prevents wind turbines in the central parts of the island from approval.
- Suggested solution: gap-filling radar.



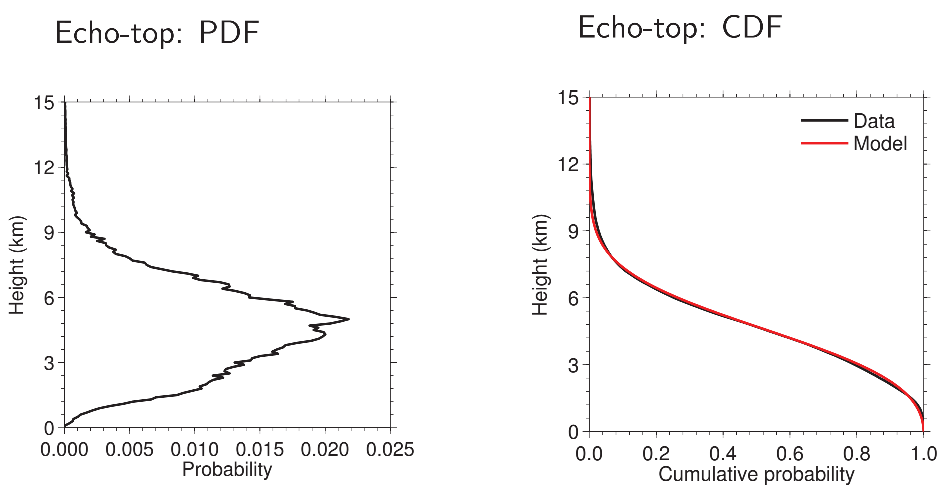
Mitigation: Gap-filling radar, constraints

- Replacing measurements must at least have comparable quality (according to SWERAD).
- Measurements over the same area can have very different quality, depending on height.
- Spatial resolution varies with distance (and protocol).



Mitigation: Measurements at different heights

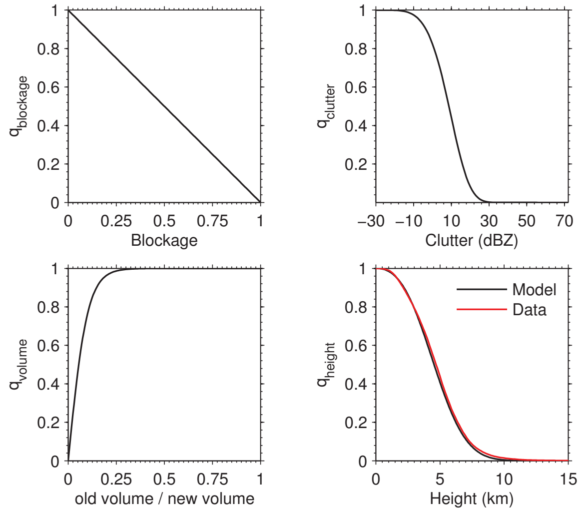
How does the quality change with respect to height?



Mitigation: Model

1. Identify impacted radar cells.
2. Find potential replacement measurements.
3. Assess quality of potential replacement measurements.

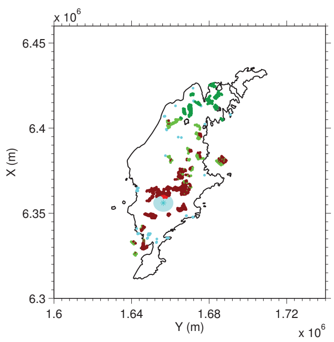
Total quality:
$q_{tot} = q_{height} \times q_{vol} \times q_{impact}$



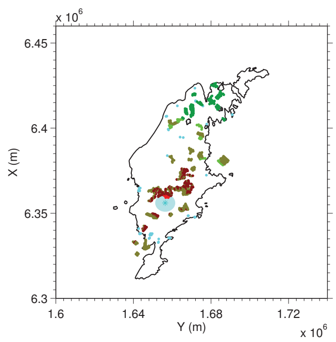
Model to be implemented by SAF later this year.

Mitigation: Test

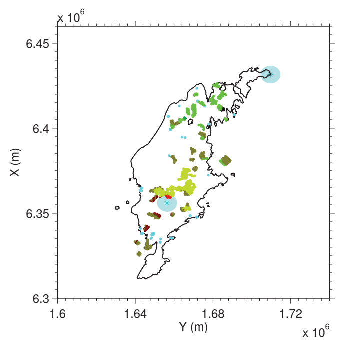
Results for > 700 fictive wind turbine applications



Old model, no gapfiller: 36% approved



New model, no gapfiller: 72% approved



New model, with gapfiller: 93% approved

Summary

- Wind turbines can have a negative impact on weather radars.
- Radar moments recover for stronger weather signals.
- Possible mitigation: gap-filling radar.

Outlook

- The Swedish weather radars are currently being modernised.
- New technology will enable access to raw (I/Q) data.
- Custom made filters can be added to signal processor.
- The possibility to implement adaptive wind turbine filters will be investigated.

Influences of Wind Energy Farms on Radar

Fraunhofer FHR

Josef G. Worms, Frank Weinmann

Fraunhofer FHR

Contents:

- Propagation Paths and Measurement Equipment
- Measurement Procedure
- Results – Propagation Path without WEA
- Results – Propagation Path with WEA
- Effects of WEA's on Measurement Data
- Preliminary Summary of Measurements

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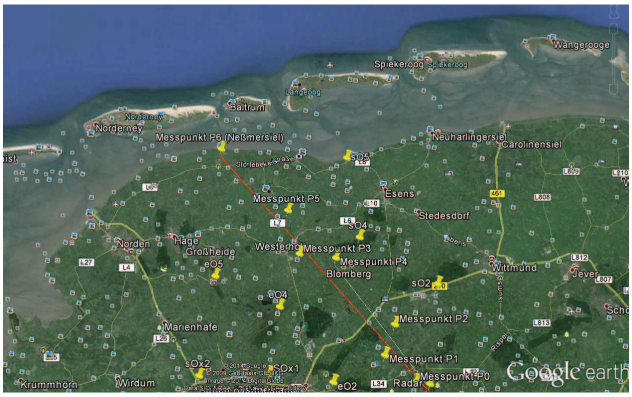
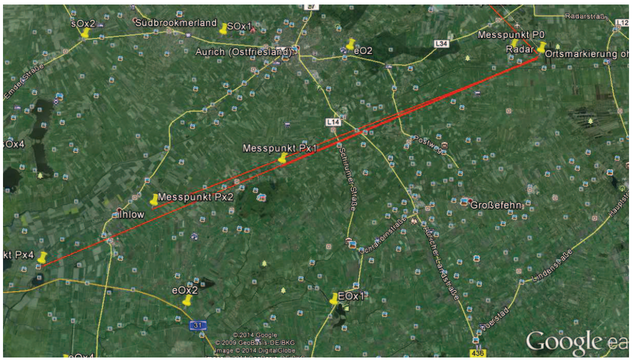
Planning of the Measurement Campaign



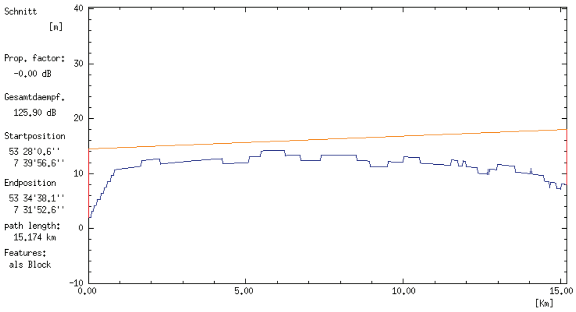
Propagation Path 1: Brockzetel - Neßmersiel

Planning of the Measurement Campaign



Propagation Path 2: Brockzetel - Emden

Planning of the Measurement Campaign

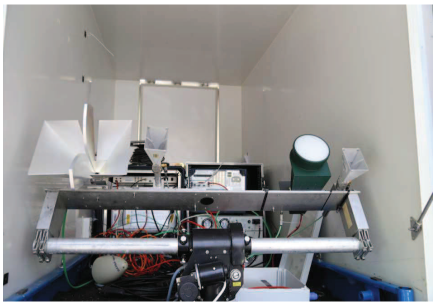


Propagation Path: Brockzetel to Measurement Point P4, Height of Receiver Antenna: 10 m (Calculated by „DARWIN“)

Ground Trials Brockzetel (May 2014)

Measurement Point P1 (at the border of wind farm Königsmoor)

Measurement Equipment



The Transmitter used during the Measurements

The second tripod based receiver used by the measurements

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Measurement Equipment

Integration of a measurement receiver including flight recorder into the FHR experimental airplane „Delphin“

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Measurements Brockzetel (May 2014)

Measuement Procedure for Ground Measurements:

- Alignment of the radar antenna with respect to the receiver (radar antenna in receiving mode)
- Two way propgation measurement: Replacement of the TWT used during calibration by a DRFM, radar antenna in transmit/receive mode
- Third step: Radar transmits pulsed signals, which are received at the measurement place by two identical receivers with antennas at heights 5m and 10m, laterally displaced

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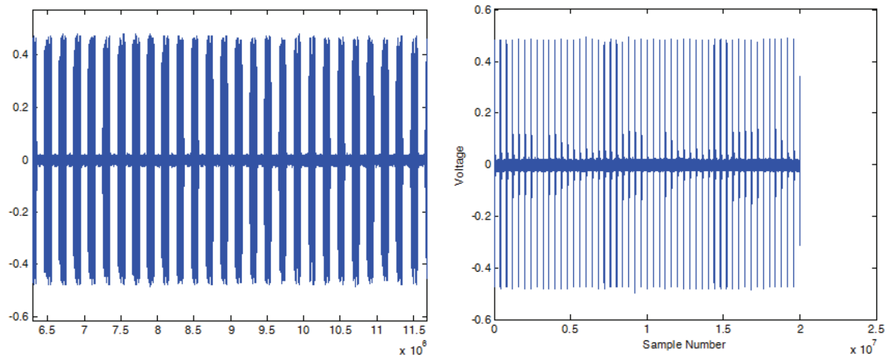
Ground Measurements Brockzetel (May 2014)



Data measured at P1 (left 2014, May 6th, right May 7th) (typical results obtained without WEA in propagation path)

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Ground Measurements Brockzetel (May 2014)

Measure-ment Point	Distance to Radar	Mean received Power	Mean Electrical Field Strength	Propaga-tion Losses	Loss Number (r^n)
Radar	0 m	-	-	-	-
P1 -Dietmar	5095.4m	-28.4295 dBm	0.8659 [V/m]	2.4849 dB	2.0670

Measure-ment Point	Distance to Radar	Mean received Power	Mean Electrical Field Strength	Propaga-tion Losses	Loss Number (r^n)
Radar	0 m	-	-	-	-
P1 (Sheldon)	5095.4m	-40.1177 dBm	0.2255 [V/m]	4.1731 dB	2.1126
P1 (Dietmar)	5095.4m	-43.6123 dBm	0.1508 [V/m]	7.6676 dB	2.2068

Measured Values at P1 (top 2014, May 6th, down May 7th)

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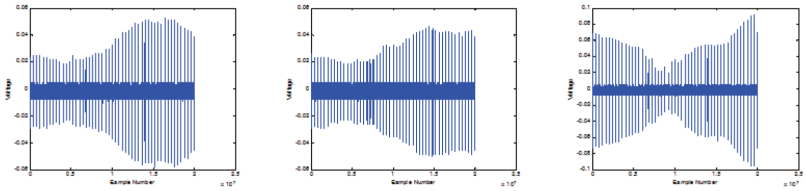
Ground Measurements Brockzetel (May 2014)

Measure-ment Point	Distance to Radar	Mean received Power	Mean Electrical Field Strength	Propaga-tion Losses	Loss Number (r^n)
Radar	0 m	-	-	-	-
P6 (Sheldon)	31253 m	-49.6681 dBm	0.0751 [V/m]	-2.0307 dB	1.9548
P6 (Dietmar)	31253 m	-46.8973 dBm	0.1033 [V/m]	-4.8015 dB	1.8932



Measurement Point P6: Comparison of 3 series of pulses

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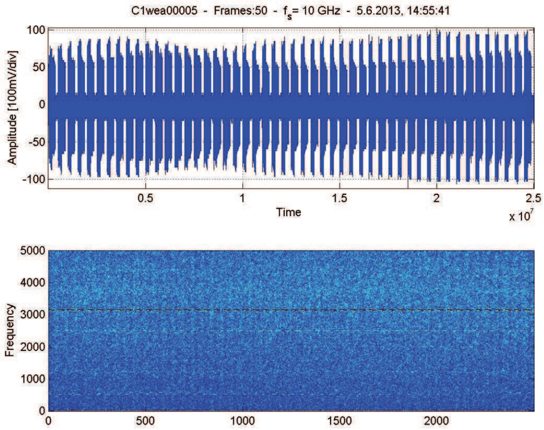
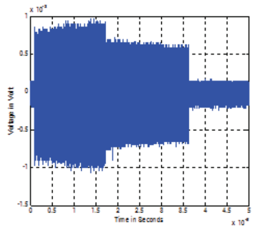
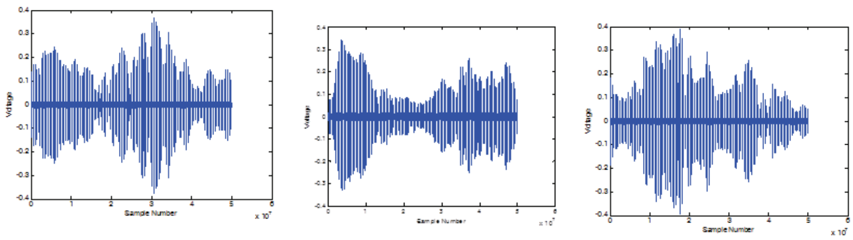




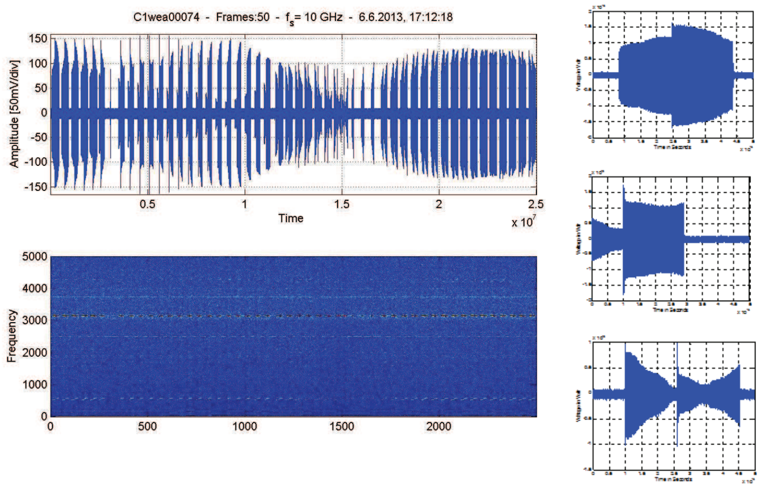
Signals at P6 (2012):
Attenuation compared to freespace: 19,9970 dB
n= 2,5191

Ground Measurements Brockzetel (May 2014)

Measure-ment Point	Distance to Radar	Mean received Power	Mean Electrical Field Strength	Propaga-tion Losses	Loss Number (r^n)
Sender	0 m	-	-	-	-
Px3 (Sheldon)	26312 m	-44.7972 dBm	0.1316 [V/m]	4.5931 dB	2.1039
Px3 (Dietmar)	26312 m	-52.0544 dBm	0.0570 [V/m]	11.8503 dB	2.2681



Measurement Point Px4: Comparison of 3 series of pulses



Signals at PX4 (2012):
Attenuation compared to freespace : 16,3909 dB
n= 2,4469

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Typical Wind Farm Simulation Scenario (Ray Tracing)

Required Developments:

- Generation of terrain CAD models from terrain data bases ☑
- Preparation of a data base of WEA CAD models ☑
- User interface for convenient generation of model and evaluation of results ☑
- Acceleration of simulations for large scenarios and large number of observation points (FARAD is optimized for RCS simulations: “small” object, 1 observation point)
- Comparison with measurements: Determine which settings and modules are required for WEA simulations (GO: quite fast, GO+PO: more accurate but very slow)

↓

- Simulation procedure: GO+PO/PTD; Calculation of total field strength ☑
- Acceleration of ray tracing algorithm (☑)
- Simplification / Approximation approaches (☑)
- Simulations in realistic environments (time-variant) ⌛

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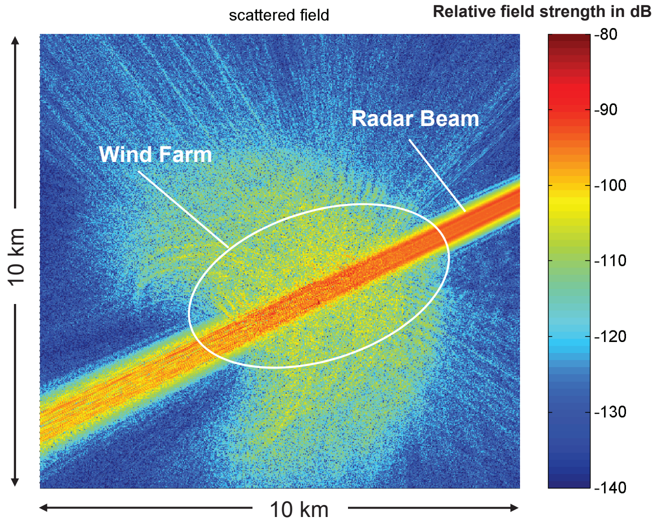
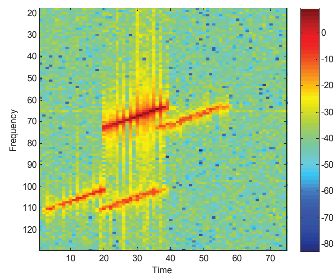
Simulation Results „WP Ihlow“ (2D Field Distribution)



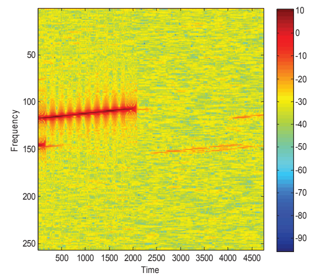
Scattered Fields

- h = 100 m
- Scattering from wind turbines
- Scattering (i.e. reflection) from dielectric smooth ground
- Results include multiple scattering
- 501x501 observation points!

Effects: Ground Measurements Brockzetel (May 2014) at Px1



Measurement 2014: Pulse repetion in ca. 40 - 50 µsec

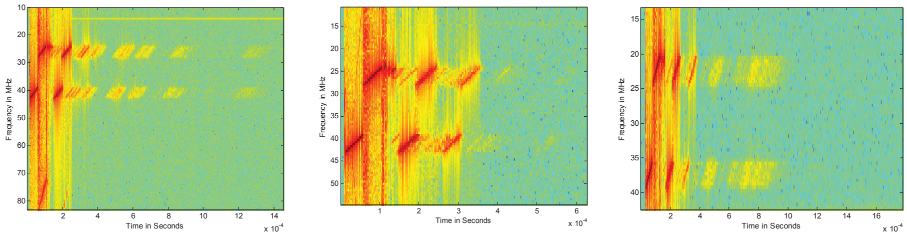


Measurement 2013: Pulse repetion in ca. 40 - 50 µsec

Proof of pulse repetition: measured 2013 and 2014 , measurement place Px1

Ground Measurements Brockzetel (May 2014)

Px1 Px2 Px3



Signals received by the radar (strong refections of the wind farm at all measurement places during one day)

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Ground Measurements Brockzetel (May 2014)

Wind farm „Ihlow“ --- Measurements 2014 (Wind turbines with different starting phases --- no lightning of the turbines observed---)

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Flight Trials Brockzetel (May 2014)

Flight trial: May 7th --- Norderney - Brockzetel

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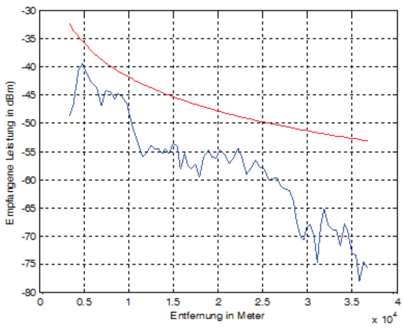
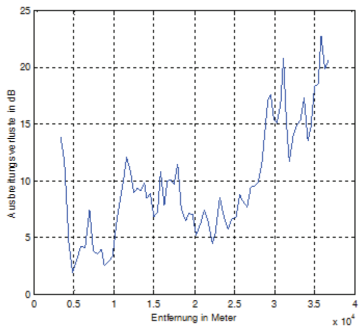
Flight Trials Brockzetel (Mai 2014)





Comparison of theoretical (red) to the measured received power (blue) with respect to the distance to th radar

Propagation losses via distance to radar

(Flight height above ground: ca. 220 m)

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Essential Results:

- Attenuation range comparable to results known from literature (ground and flight trials)
- New: Observed Fluctuations of pulse power over time
- New: Change of pulse modulation caused by WEA
- Effects observed in 2013 confirmed in 2014
- Measured effects were verified by theoretical investigations (F. Weinmann, FHR-AEM)

In particular:

- Hight cuts
- Because of the bad weather, measurements near freespace (without influences of ground) were repeated in November 2014 (flight trials)
- Measurement in greater distance

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IFT&E Summary and Wind – Radar Interference Mitigation R&D

Jason C. Biddle, MIT Lincoln Laboratory

IEA 83rd Topical Experts Meeting
Fraunhofer FHR, Wachtberg, Germany
6-7 October 2015

IFT&E: Interagency Field Test and Evaluation

This work is sponsored by DOE and DoD under Air Force Contract #FA8721-05-C-0002. Opinions, interpretations, recommendations and conclusions are those of the authors and are not necessarily endorsed by the United States Government.

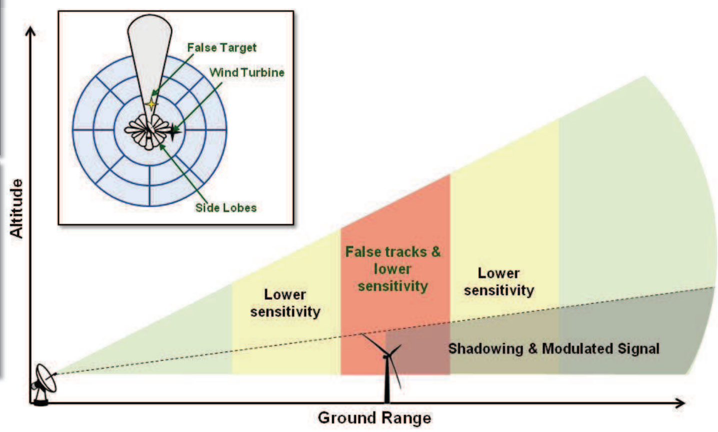
Wind Turbine Impacts

Turbines are growing in size and number

- Tip speeds over 225 mph
- Blades more than 50 m long
- 30 – 40 dBsm
- Wind farms with 100s of turbines

- Decreased Sensitivity (P_D)
- False Targets (P_{FA})
- Corrupted Track Quality

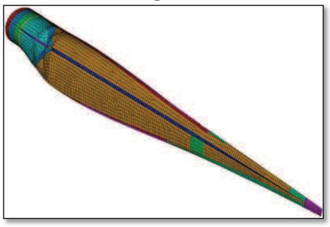
Concern for:
- Flight Safety
- Homeland Air Security



IEA TEM – 2
6-7 Oct 2015

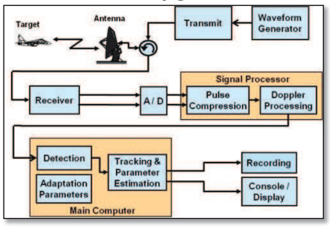
Industry Proposed Mitigation Options

Reduced Signal Turbines



Replacement Radar

Radar Upgrades



Wind Farm Siting

Augmentation Radar

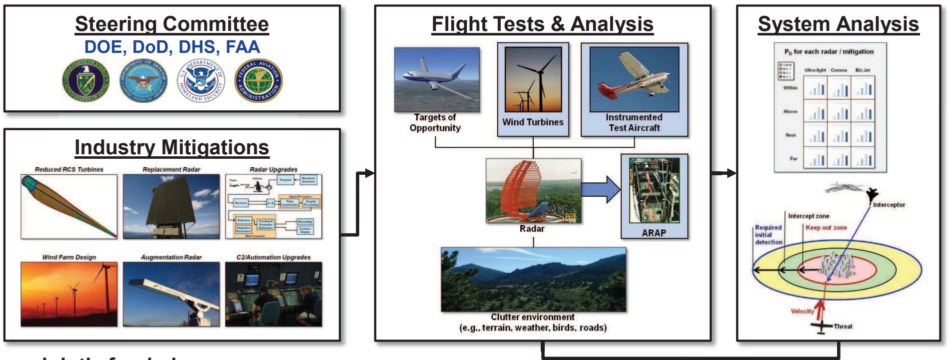
C2/Automation Upgrades

IEA TEM – 3
6-7 Oct 2015

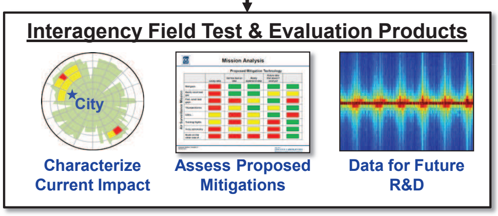
Approved for Public Release
Group Code # 403579
SAND # 221757

Interagency Field Test & Evaluation

Evaluate wind turbine impact and industry mitigations



- 2-year, jointly funded program
- 3 flight campaigns
  - CARSR (Tyler, MN)
  - ASR-11 (Abilene, TX)
  - ARSR-4 (King Mountain, TX)
- Invite selected mitigations
  - Selected 11 concepts to assess
- System analysis of mission impact



IEA TEM – 4
6-7 Oct 2015

Approved for Public Release
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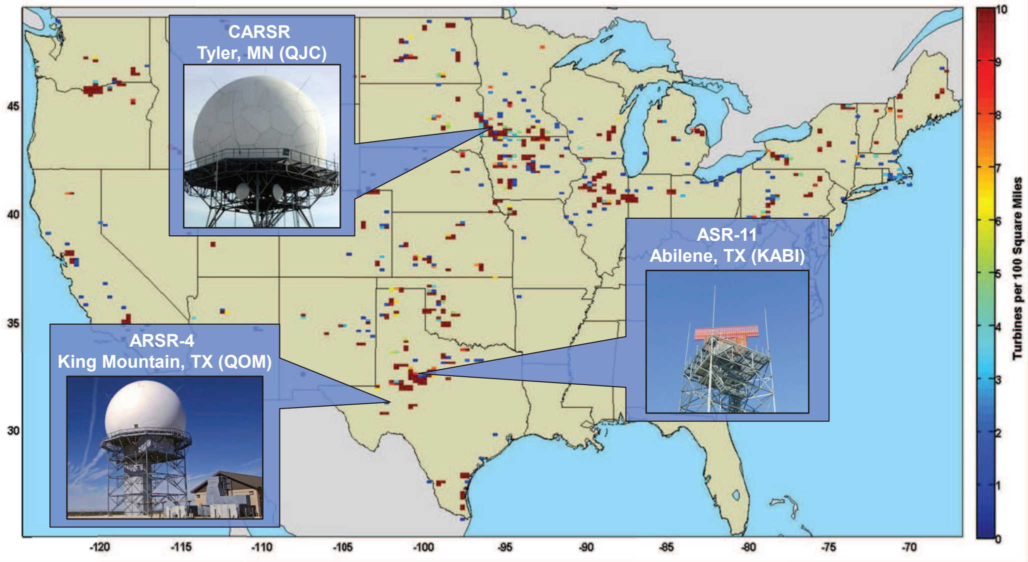
SAND # 221757

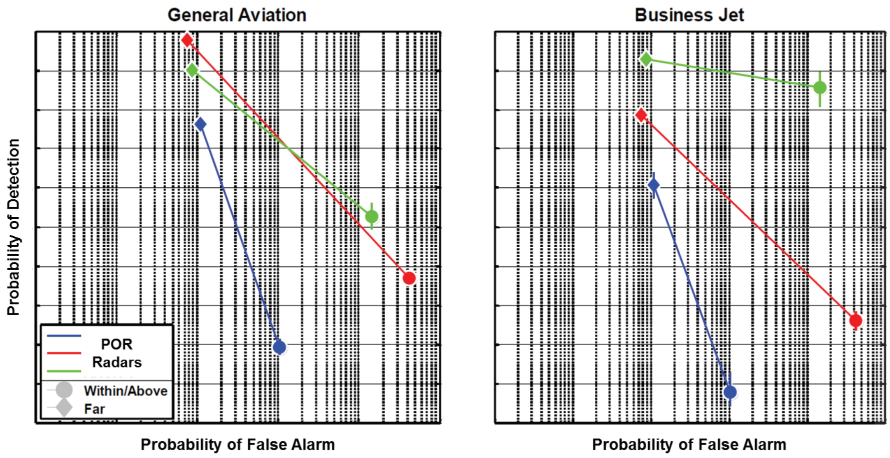
IFT&E Flight Campaigns



IEA TEM – 5
6-7 Oct 2015

Approved for Public Release
Group Code # 403579
SAND # 221757

Performance of Existing Radars



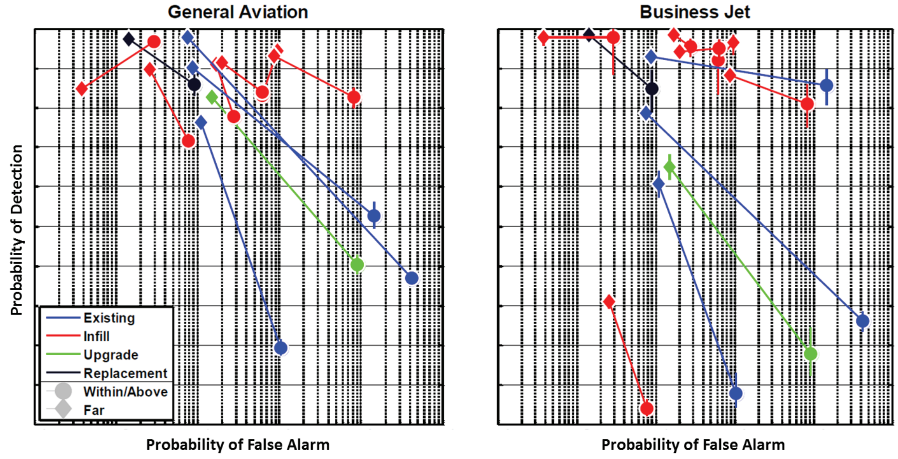
Existing primary surveillance radar performance significantly impacted in regions near and above operating wind turbines

SOURCE: IFT&E Industry Report: Wind Turbine – Radar Interference Test Summary, SAND2014-19003, Sep 2014
http://energy.gov/eere/wind/downloads/interagency-field-test-evaluation-wind-turbine-radar-interference-mitigation

IEA TEM – 6
6-7 Oct 2015

Approved for Public Release
Group Code # 403579
SAND # 221757

Performance of Existing Radars and Tested Mitigations



All systems tested were impacted by wind turbines; however, many of the mitigation systems were significantly less impacted than existing radars

SOURCE: IFT&E Industry Report: Wind Turbine – Radar Interference Test Summary, SAND2014-19003, Sep 2014
http://energy.gov/eere/wind/downloads/interagency-field-test-evaluation-wind-turbine-radar-interference-mitigation

IEA TEM – 7
6-7 Oct 2015

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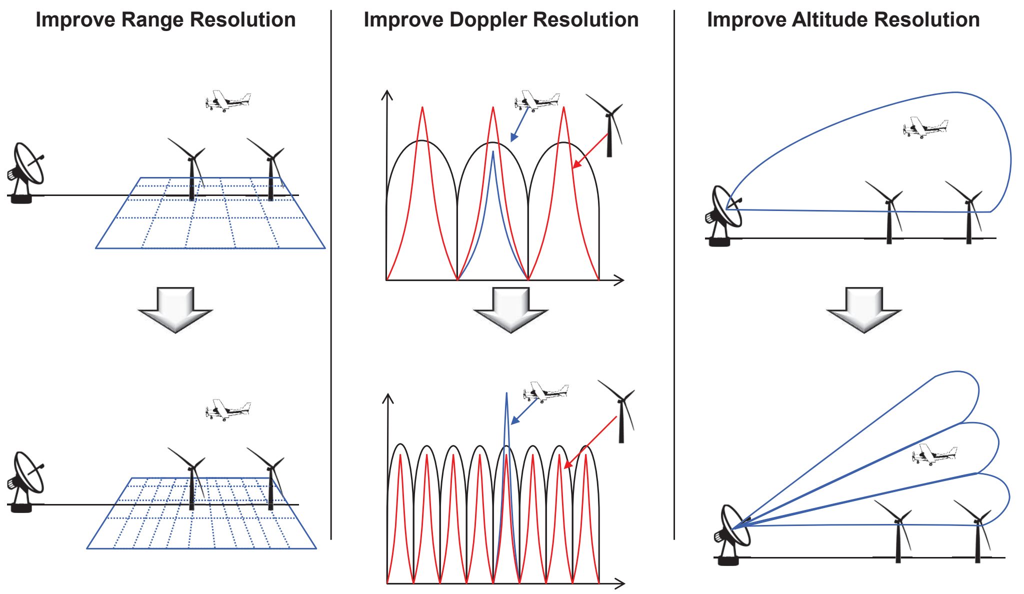
Radar Approaches to Improving Detection



IEA TEM – 8
6-7 Oct 2015

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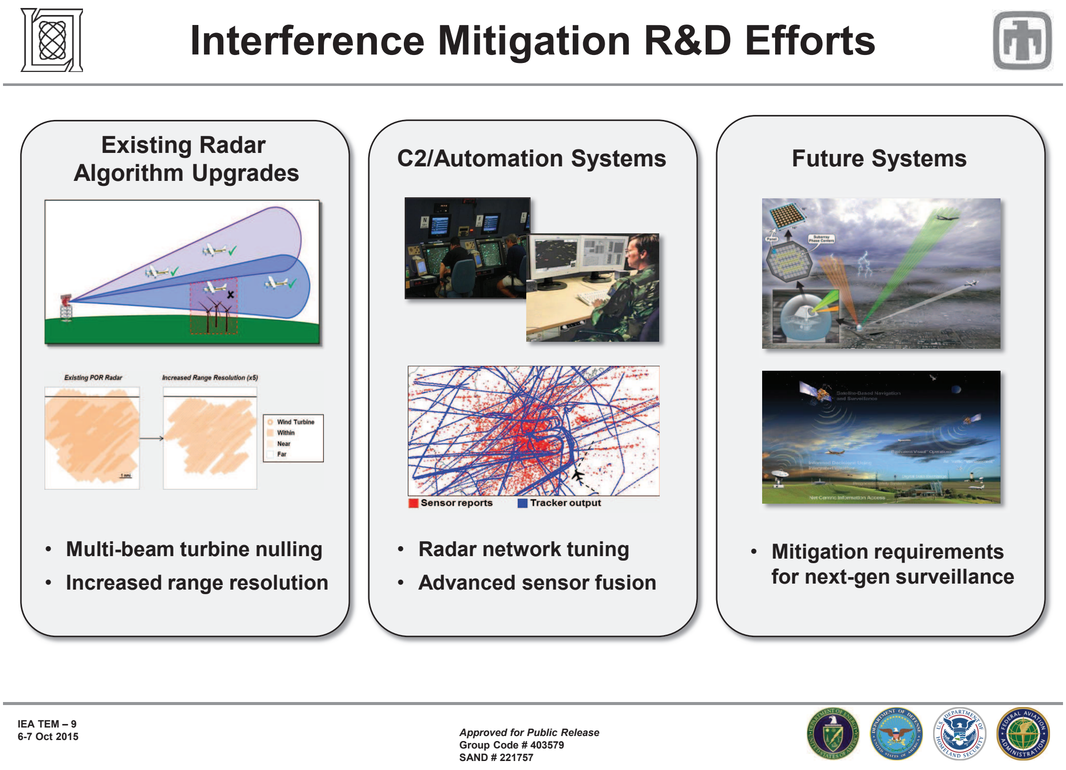
Interference Mitigation R&D Efforts
Existing Radar Algorithm Upgrades
Multi-beam turbine nulling
Increased range resolution
C2/Automation Systems
Sensor reports
Tracker output
Radar network tuning
Advanced sensor fusion
Future Systems
Mitigation requirements for next-gen surveillance
IEA TEM – 9
6-7 Oct 2015
Approved for Public Release
Group Code # 403579
SAND # 221757

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CONTENT

- Dutch regulations
  - Old and new
- Main features PERSEUS radar performance modelling
- Impact new method on wind turbine interference assessments
- Some examples
- Complementary tooling for secondary radar

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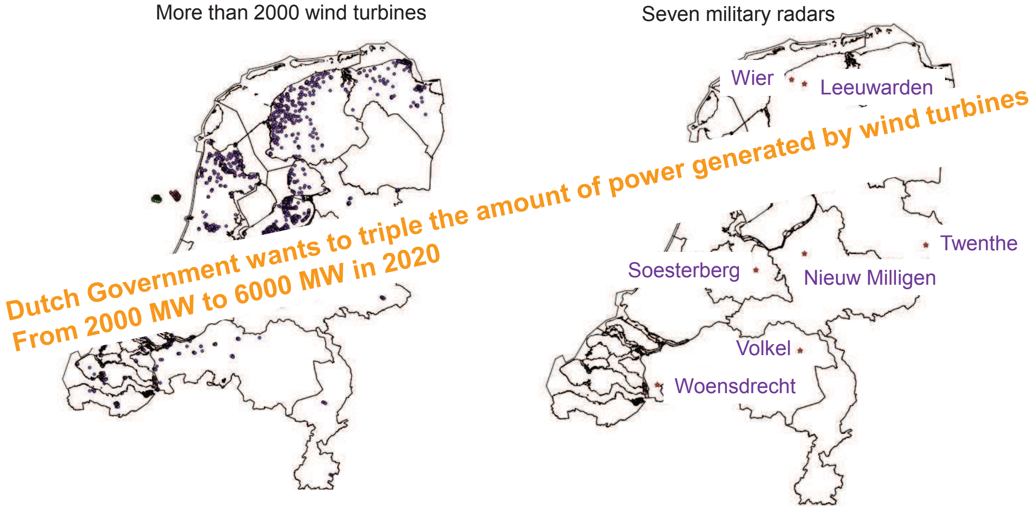
SITUATION IN THE NETHERLANDS JANUARY 2015

More than 2000 wind turbines

Seven military radars



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ON THE OTHER HAND....

- Densely populated country, with lots of aerospace activity (both civil and military) and lots of wind.
- All flat country.
- Small country (approx. 200 x 300 km or 120 x 200 miles) in relation to typical radar ranges, hence many issues for only a handful of radars
- Wind farm – radar interaction still a major issue, but solutions available.

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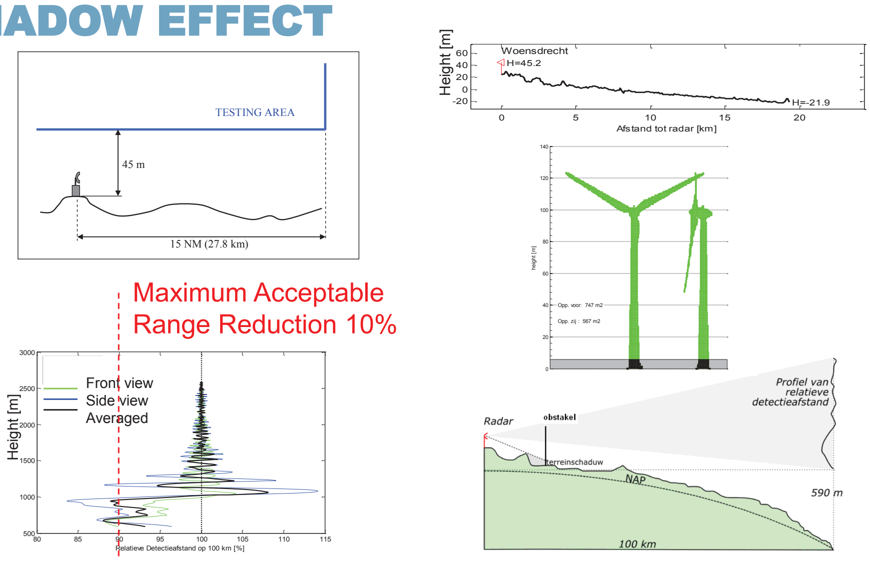
OLD ASSESSMENT METHOD IN THE NETHERLANDS ONLY ADDRESSED THE SHADOW EFFECT



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LIMITATIONS OF OLD PROCEDURE

- Only addresses the shadow effects and not the reduction of detection above a wind turbine caused by (Doppler) reflections of the wind turbine blades.
- In case of multiple wind turbines only the wind turbine at closest range to the radar was assessed.
- Processing improvement in the radar receiver or other special features, such as a 3D radar, were not taken into account.
- Radar fusion was not supported.

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PERSEUS DEVELOPMENT AT TNO

- Defence Research Laboratory established at Waalsdorpervlakte, The Hague before WW2.
- By mid 1980 Defence Research merged into TNO organisation
- TNO is a not-for-profit organisation established by law
- Since 1995 TNO investigates the effects of wind turbines on Defence radars and develops assessment methods.
- Most recent is PERSEUS (**P**rogram for the **E**valuation of **R**adar **S**ystems in an **E**xtended **U**rban **S**etting) sponsored by Ministry of Defence as well as Ministry of Infrastructure and Environment.

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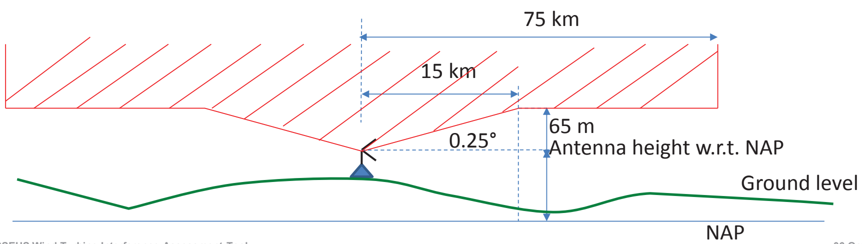
NEW ASSESSMENT CRITERIA WIND TURBINES

- Assessment criteria **wind turbines** restriction area:
  - The tip of the blade (i.e. maximum height of turbine) must not stick though a cone around a radar position, otherwise it must be assessed by TNO
  - Cone angle 0.25º starting at primary radar antenna height
  - Cone diameter 15 km
  - Between 15 km and 75 km tip of blade not higher than 65 m + primary radar antenna height, referenced to NAP



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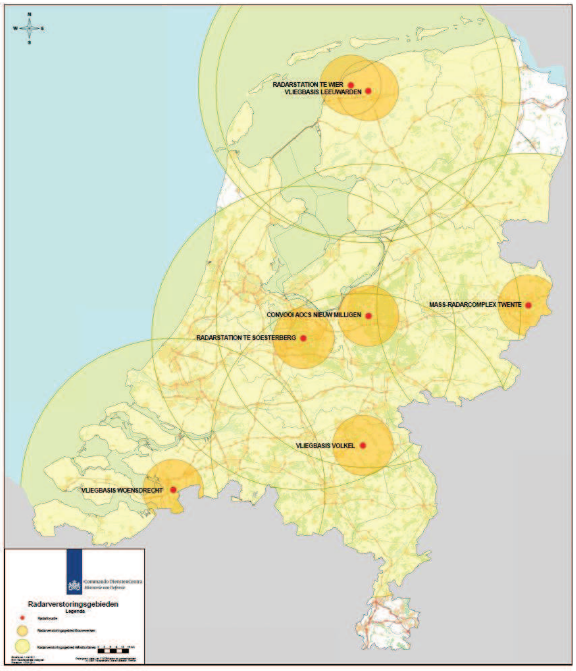
15 & 75 KM ZONES

- Military Air Traffic Control radars (2D):
  - Leeuwarden
  - Soesterberg
  - Twenthe
  - Volkel
  - Woensdrecht
- Military Fighter Control radars (3D):
  - Nieuw Milligen
  - Wier



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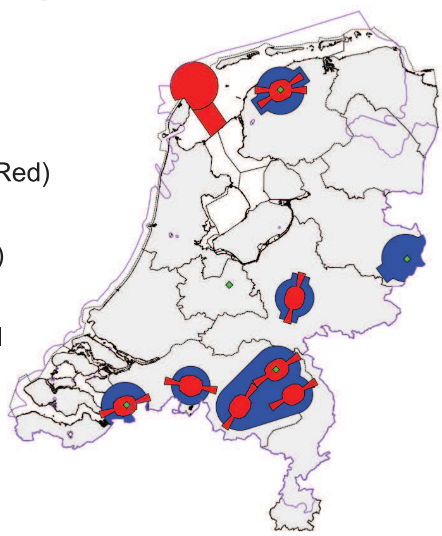
RESTRICTION AREAS FOR MASS AIR TRAFFIC CONTROL RADAR NETWORK AROUND MILITARY BASES

- IHCS and airstrip funnels: 300 ft or ≈ 91 m (Red)
- CTR: 500 ft or ≈ 152 m (Blue)
- Overall coverage: 1000 ft or ≈ 305 m Purple)

- Note: Heights are referenced to ground level



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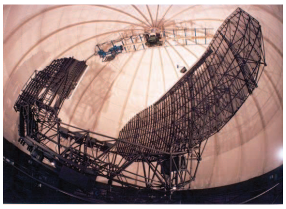
MILITARY RADARS INVOLVED

- Military Air Traffic Control (2D)
  - Commercial Raytheon ASR-10SS-upgrade

- Military Fighter Control (3D)
  - Classified radar performance



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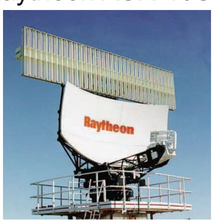
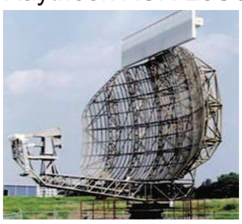
OTHER RADAR MODELS IN OUR INVENTORY

Selex ATCR-33K

Raytheon ASR-10SS



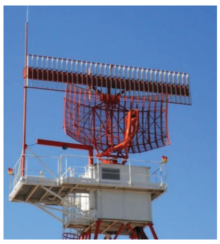
Raytheon ASR-23SS



Thales SMART-L EWC GB

Thales SMART-S Mk2

Thales STAR 2000



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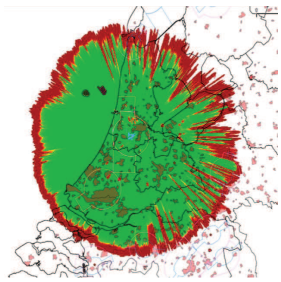
MODELLING WIND TURBINES

- Based on 3D CAD drawings provided by wind turbines manufacturers:
  - Alstom
  - Darwind
  - Enercon
  - EWT
  - Gamesa
  - Lagerwey
  - Nordex
  - Senvion (previous REpower)
  - Siemens
  - Vestas

PERSEUS TOOLKIT SUMMARY



- Compliance with existing guidelines
  - ICAO EUR DOC 015 (2009)
  - CAA CAP 764 (2010)
  - Eurocontrol WTTF (2010)
- For PSR only; Complementary tooling for SSR
- Wind turbine static & moving parts
- Desensitization Overhead: CFAR processing & pulse compression
- Shadow Effect
- Multiple-radar data fusion, gap fillers
- Line-of-sight and diffraction (TERPEM) based on SRTM terrain height database
- Volumetric assessment
- Versatile radar modelling (based on TNO's CARPET, with 500+ licenses sold worldwide)

PERSEUS IS BREAKING THE STALEMATE

- PERSEUS proved effectiveness of Raytheon ASR-10SS upgrade, which led to the wind farm industry funding the upgrade
  - The Kreekrak wind farm, near (8 km) Woensdrecht air base
- By better showing effects on radar, including CFAR filtering
- And by modifying the radar in co-op with manufacturer, and funding from the wind industry.

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INTERNATIONAL CUSTOMERS

- Belgium : EUROCONTROL WTTF Guidelines Simple and Detailed Engineering Assessments (SEA & DEA) for different customers which has been assessed by Belgocontrol and Belgium Airforce
- Curacao: Wind turbine interference assessment for primary and secondary radar and other navigation and communication system at Hato Airport.
- United Kingdom: Wind turbine interference assessments for primary radar for an on-shore wind farm customer and an off-shore wind farm customer.

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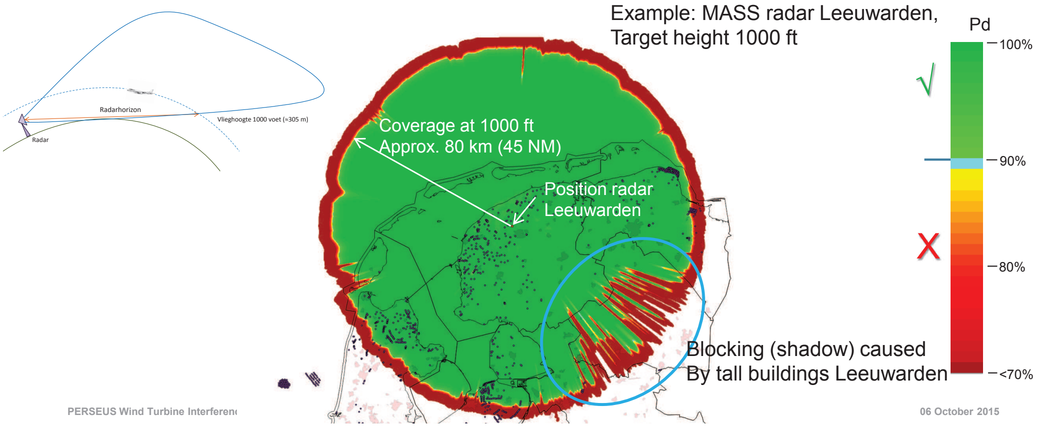
PERSEUS RADAR PERFORMANCE CALCULATIONS

- Single scan detection probability (Pd) of a target (aircraft) having a radar cross section (RCS) 2 m^2 at a target height of 300, 500 and 1000 ft.



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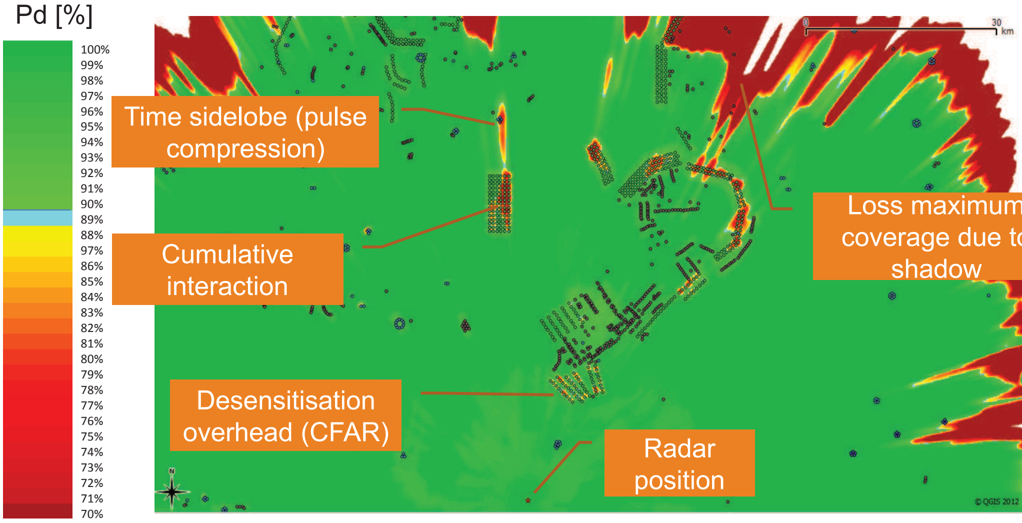
PERSEUS RADAR COVERAGE DIAGRAM (1000 FT) INCLUDING WIND TURBINE INTERFERENCE EFFECTS



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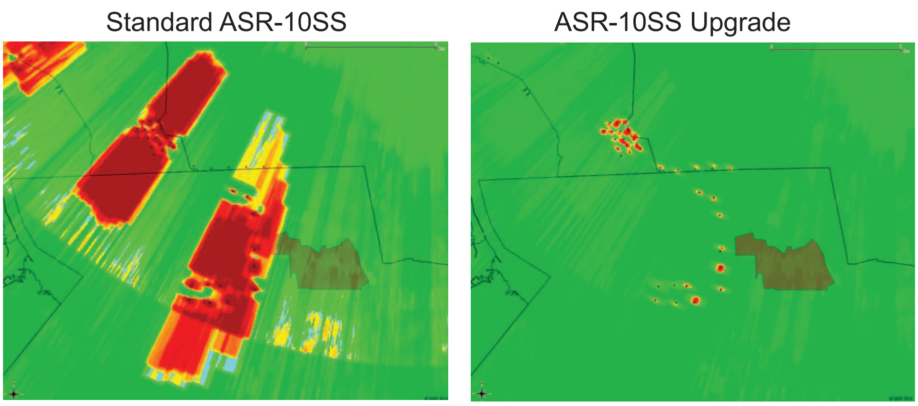
IMPROVEMENT OF RADAR PROCESSING. STANDARD RAYTHEON ASR-10SS V.S. UPGRADED



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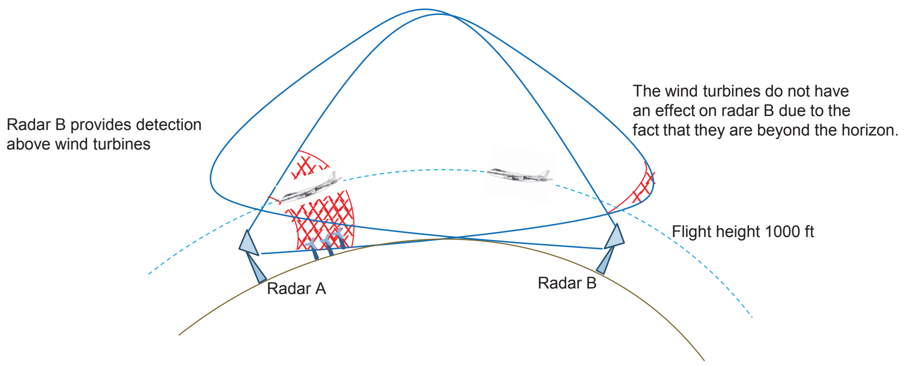
DATA FUSION OF MULTIPLE RADARS IN SAME RADAR NETWORK E.G. ARTAS* OF EUROCONTROL



*ATM suRveillance Tracker And Server

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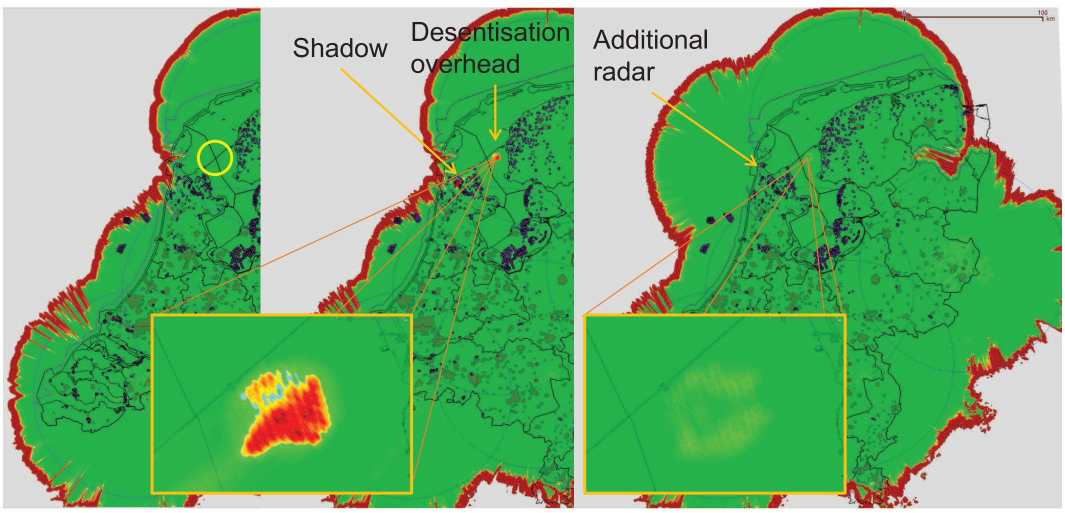
WINDFARM 96 TURBINES. PROVE BENEFIT OF AN ADDITIONAL RADAR AT DEN HELDER



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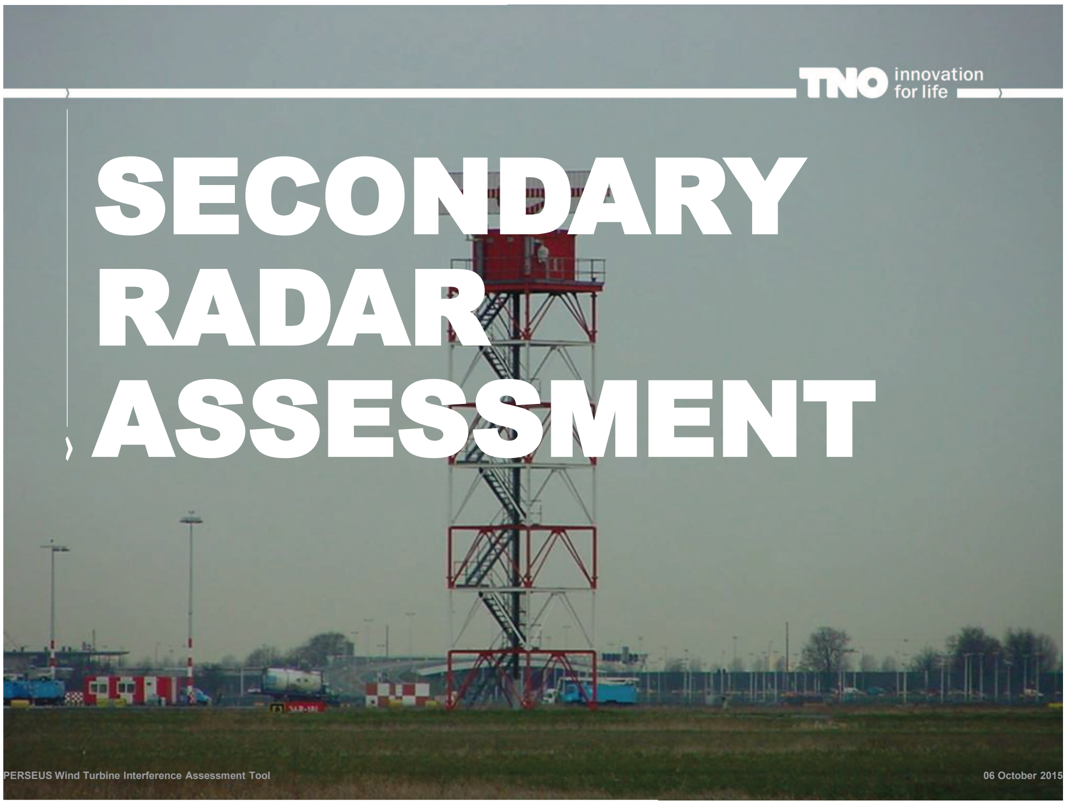

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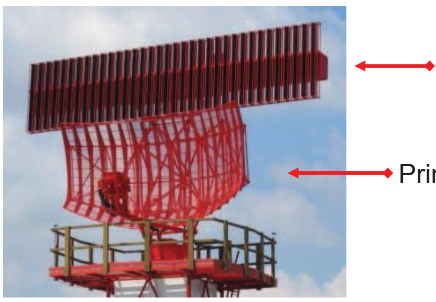
SECONDARY RADAR

- Civil application radar, used for air traffic control
- Cooperative system: dependent on transponder on board of the aircraft
- SSR provides additional information (ID, altitude, etc.)
- In case of monopulse SSR (MSSR), system also capable of accurate estimation of target bearing (typical within ~0.05˚)



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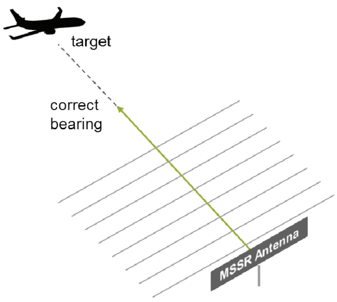
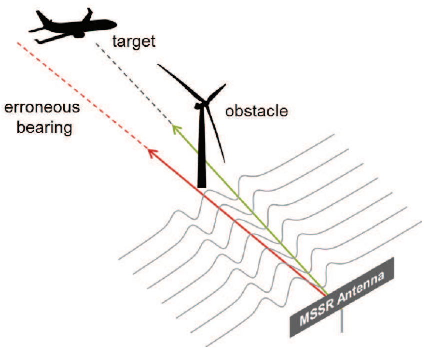
MSSR BEARING ERROR

- Wind turbines, positioned between target and MSSR antenna can disturb the transponder signal, introducing an error in the bearing estimate
- TNO has developed tooling to quantify the bearing error





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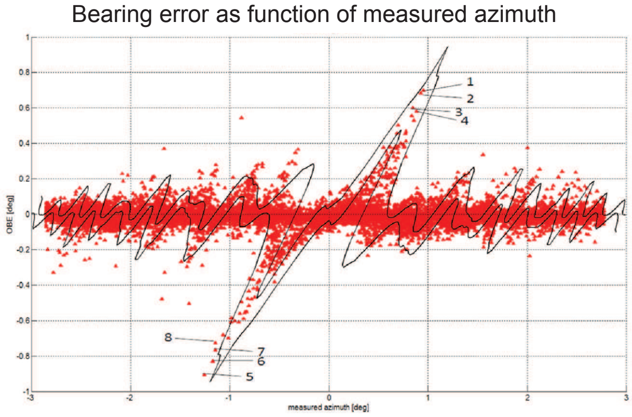
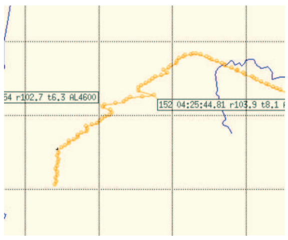
MSSR TOOLING: VALIDATION

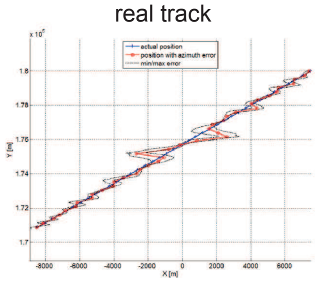
Bearing error as function of measured azimuth



real data (**red dots**), TNO model (**black line**)



real track



simulated track

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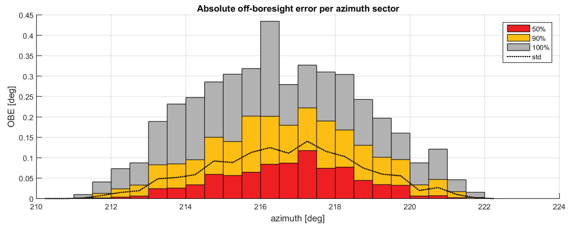
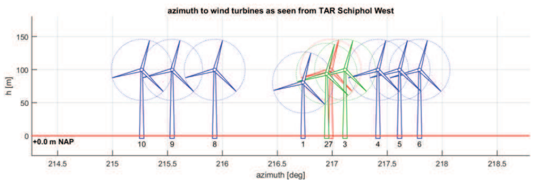
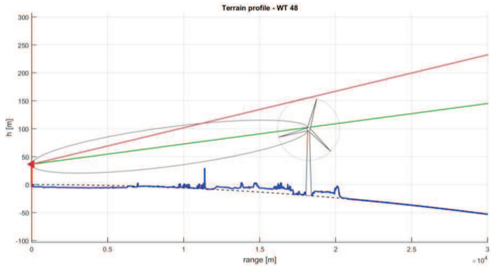
MSSR TOOLING: RESULTS

- Multiple wind turbines
- Line-of-sight analysis
- Digital elevation model (DEM)







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CONCLUSION

- The Netherlands created a successful assessment and mitigation scheme
- With a central role for TNO, to break stalemate and bring together conflicting government & industrial interests
- A variety of mitigations is feasible
- Advanced tooling by PERSEUS
- TNO willing & able to co-operate with international partners

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CONTACT INFORMATION

- Technical issues and requests for formal assessments:
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    - Email: onno.vangent@tno.nl
- Any other issues:
  - Michiel Ringers
    - Telephone: +31 (0)88 86 63 989
    - Email: michiel.ringers@tno.nl
  - Visiting address:
    - TNO The Hague
    - Oude Waalsdorperweg 63
    - The Hague

See also: www.tno.nl/perseus

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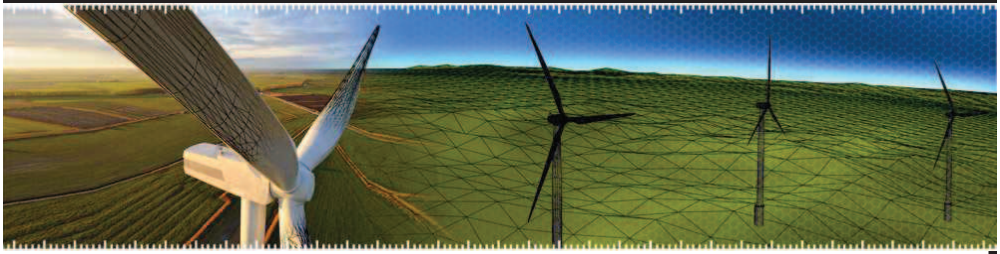

Wind Farm vs Radar:

The importance of site specific wind farm modelling in radar impact assessments

Prof Anthony Brown

Dr Laith R Danoon

The Microwave and Communication Systems Research Group

School of Electrical and Electronic Engineering

The University of Manchester

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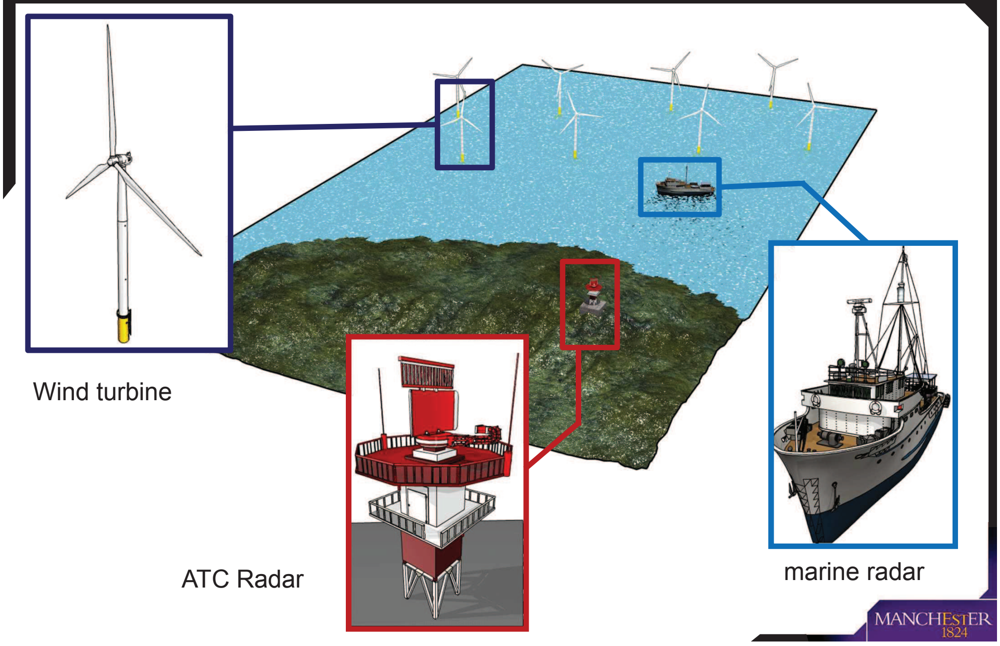
Wind Farms and Radars



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Interference Overview

- The development of wind farms in areas which causes radar interference is seen as a significant threat to safety and security
- Defence and Air Traffic Control (ATC) radars lose sensitivity and the ability to detect objects over the wind farm
  - Due to the large radar echoes
  - Due to the Doppler signature generated by the rotating blades
- Marine based radars and coastal Vessel Tracking Systems (VTS) are affected by the large echoes and the multiple reflections of the radar signal within the wind farm and shadowing

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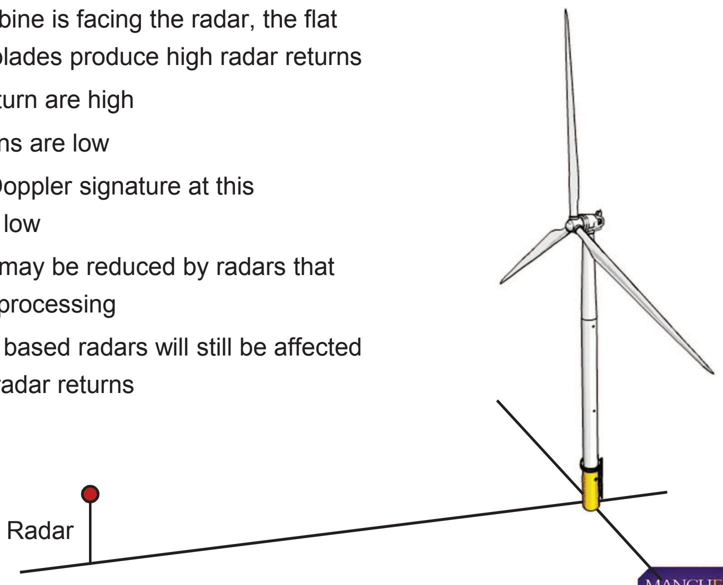
Interference with Radar

- When the turbine is facing the radar, the flat sides of the blades produce high radar returns
- The tower return are high
- Nacelle returns are low
- The overall Doppler signature at this orientation is low
- High returns may be reduced by radars that use Doppler processing
- Non-Doppler based radars will still be affected by the large radar returns



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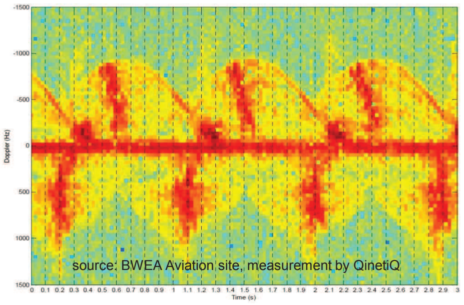
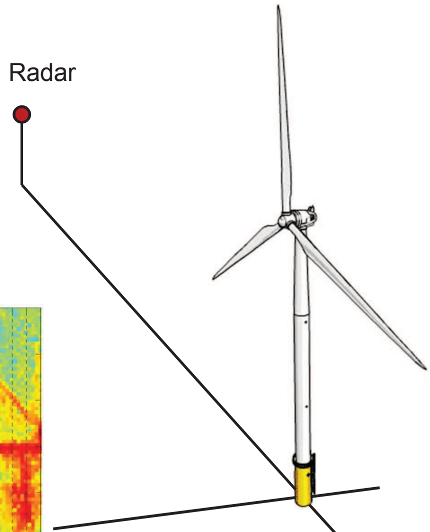
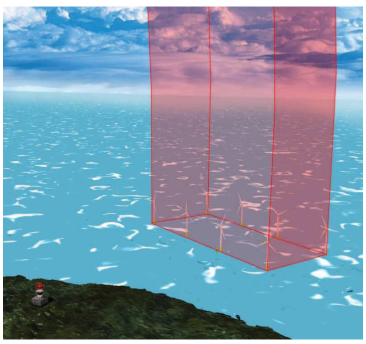
Modelling Challenges

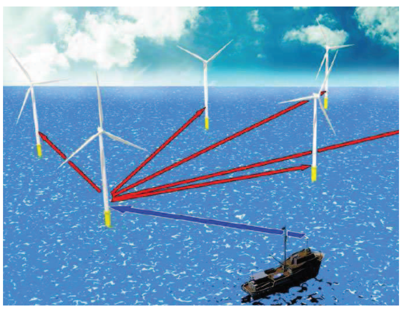
- Side illumination may give lower returns depending on the turbine geometry
- Blades tend to have lower RCS at such orientation
- Tower RCS remains the same
- Nacelle RCS is high
- Doppler returns from the blades are high
- May have a wide Doppler spectrum

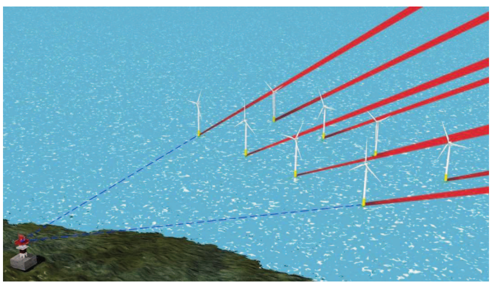


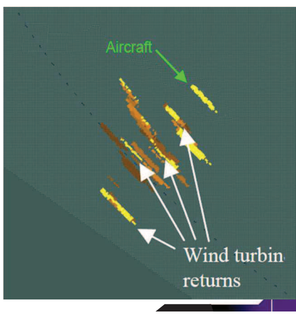


Common Issues

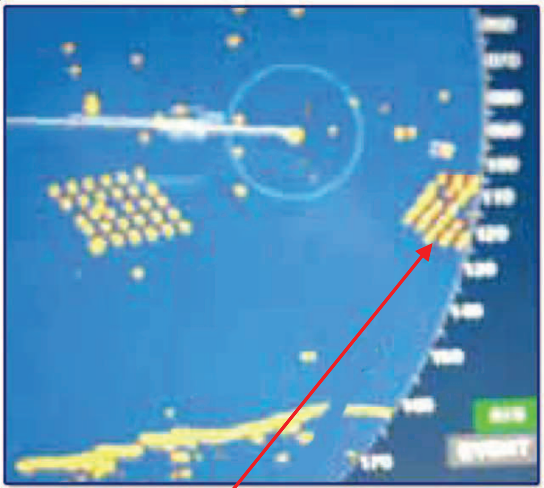








High Level Reflections



The appearance of mirror image of the wind farm due to reflection from the ship's structure

*Picture: courtesy of MARICO Marine

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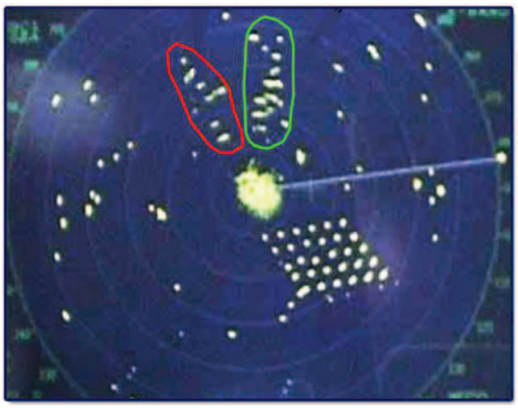
Multiple Reflections From Large Targets



Reflections from a near by car-carrier

Reflections from Shivring Sands towers

*Picture: courtesy of MARICO

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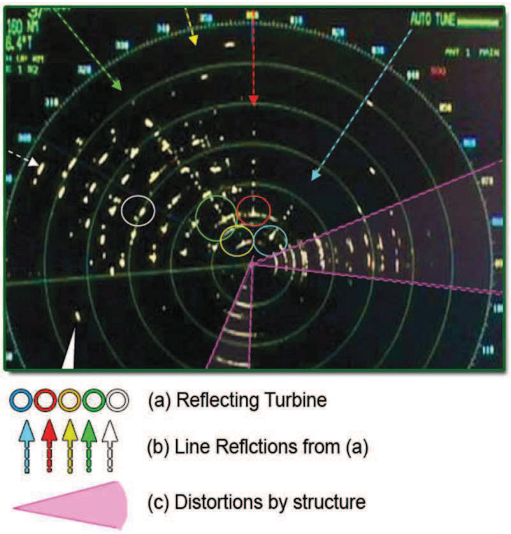
Combined Effects



*Picture: courtesy of MARICO

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Modelling Challenges (1)

- Complexity of the interaction
- Physical size is big, electrical size is huge!
- The interaction might be different for every wind turbines, wind farms layout, radar and location
- Pseudo random nature of the blade rotations in the wind farm makes it difficult to predict all possible outcomes
- Various external parameters affecting the interaction
- Interaction with local environment

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Mitigation Options

- The interference of wind farms with radar systems arises when the wind farm is located within a high impact zone (ie, within the line of sight of safety critical radars)
- Through early engagement and discussions with the radar operators and other stakeholders, wind developers can address these and possible solutions may be available
- Depending on the nature of the objection, the issues may be overcome through simple and cost effective measures
- The nature of these mitigation solutions can be categorized into a technical intervention and a non-technical intervention

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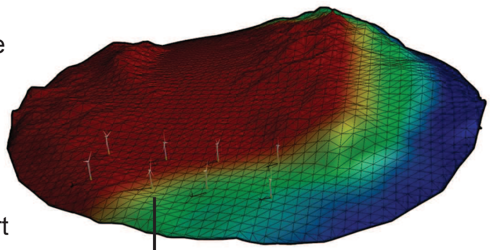
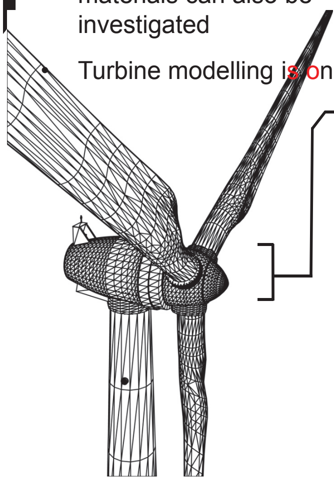
Wind Farm and Radar Modelling

- Accurate turbine geometry for radar scattering modelling can be used
- The effect of radar absorbing materials can also be investigated
- Turbine modelling is only the start





- The aim is to model a complete *wind farm* for site/radar specific assessment
- Environmental and inter-turbine interaction modelling
- Modelling the effects of local terrain
- Computational efficiency for rapid assessment of possible impact

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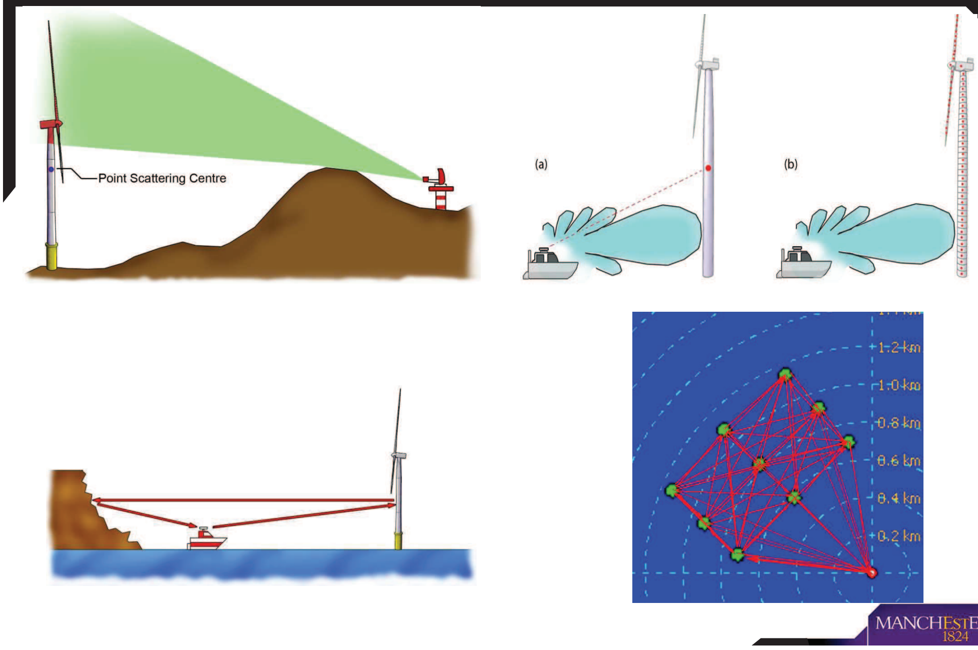
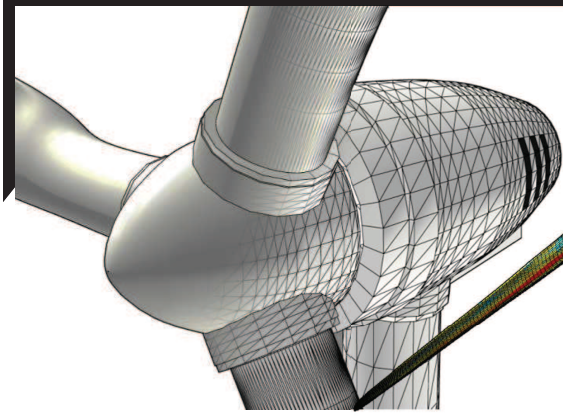
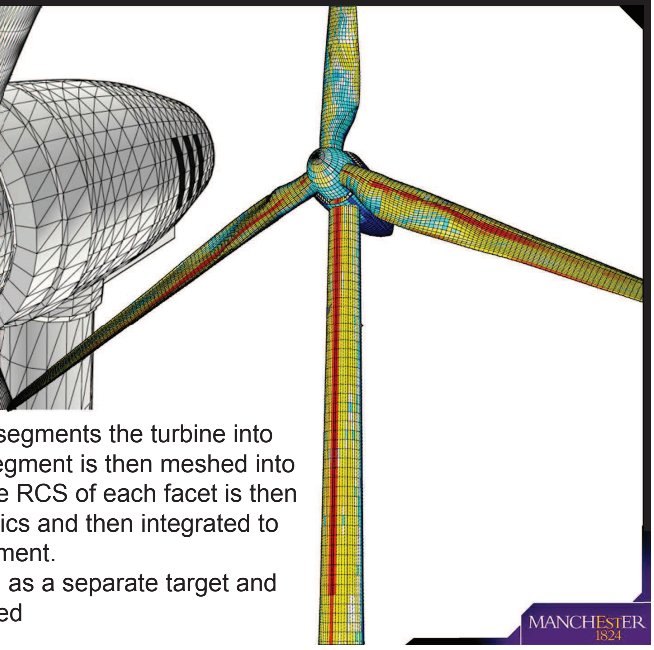
Radar Interaction Modelling

- To overcome some of the limitations faced by other wind farm studies and wind turbine RCS modelling
  - RCS variation with range to radar
  - Effects of partial shadowing
  - Non-uniform illumination of turbine
  - Wind FARM modelling vs wind TURBINE modelling
  - Effects from multiple reflections and shadowing from local terrain
- Quick modelling run-times to enable the study of different wind farm layouts and sites and multiple scenarios

Overcoming modelling limitations



Turbine Radar Scattering

The radar scattering models segments the turbine into smaller components. Each segment is then meshed into small quadrilateral facets. The RCS of each facet is then computed using Physical Optics and then integrated to give the total RCS of the segment.
Each segment is then treated as a separate target and the radar returns are calculated

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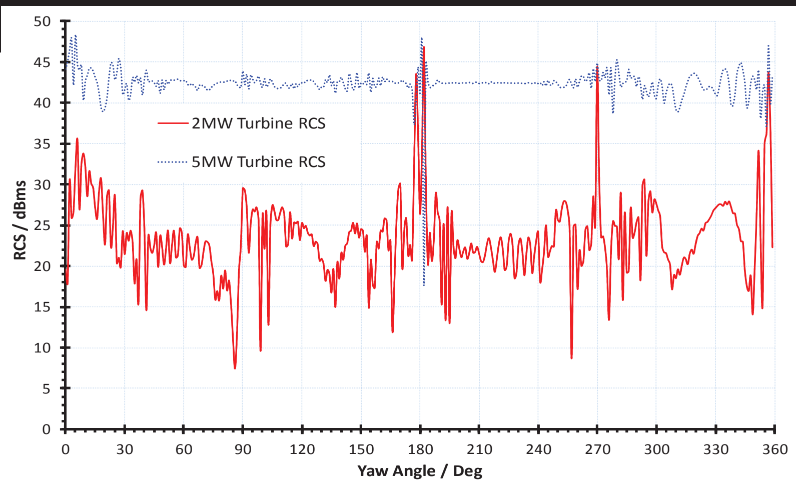
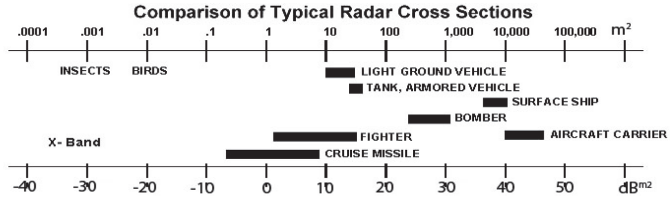
Turbine Radar Cross Section





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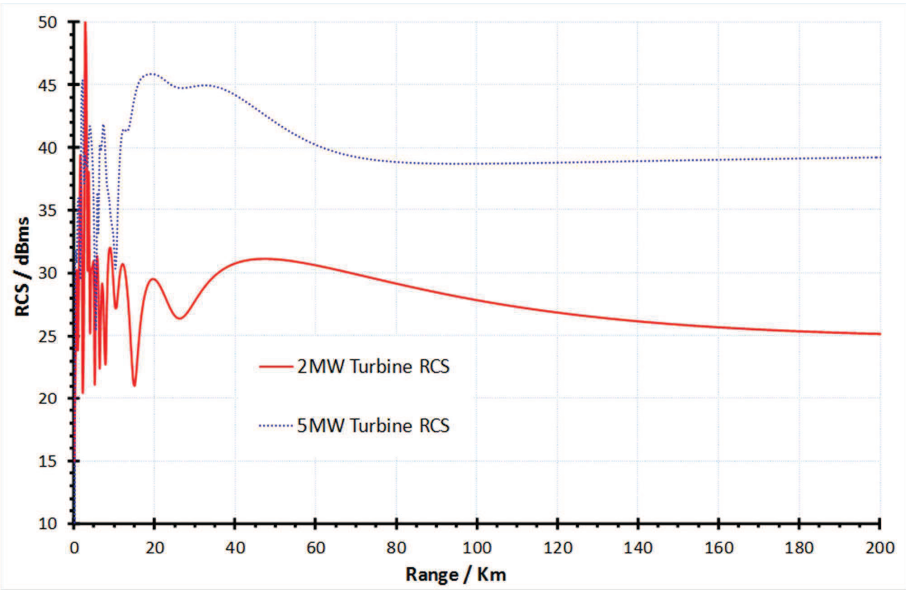
Turbine RCS variation with range

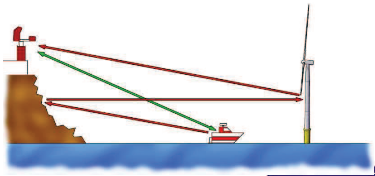
- RCS studies often give the RCS of the turbine based on its FARFIELD range conditions
- It is worth noting that the farfield distance for a typical wind turbine is 240km at S band (3GHz) and 800km at X band (9 GHz)
- This can be beyond the operational limits of the radar
- It is important to account for the variation of RCS for radars operating within 10’s of kilometres
- Nearfield effects may significantly affect the RCS profile and the Doppler signature

Turbine Scattering vs Range



Terrain Effects Modelling

- Terrain profile near the radar and the wind farm may significantly affect the interaction.
- Siting wind farms in areas that are shadowed by local terrain may greatly reduce the potential impact
- Terrain may also cast a partial shadow over the turbine structure causing the turbine scattering to be altered
- Steep cliffs and coastal features may add to the multiple reflections effects
- Terrain modelling is important to include for onshore wind farms and for offshore wind farms and radars based close to the coast



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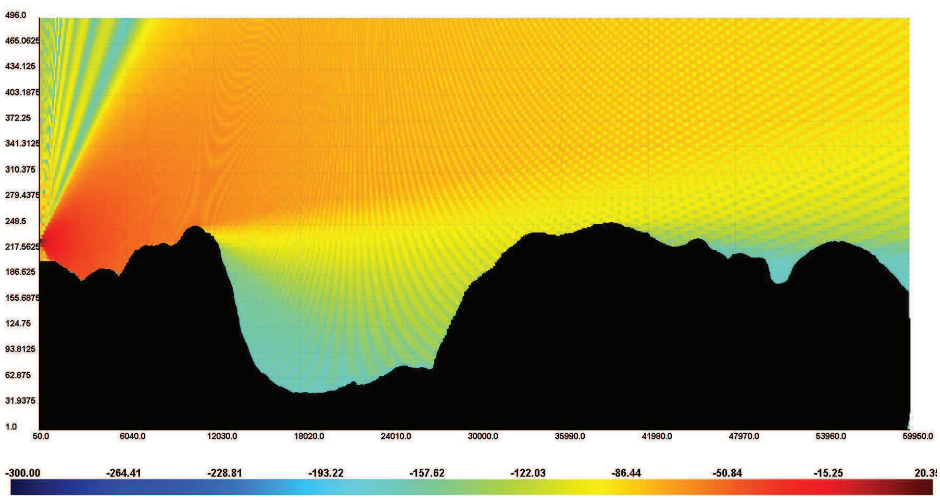
Wind farm and environment – Terrain



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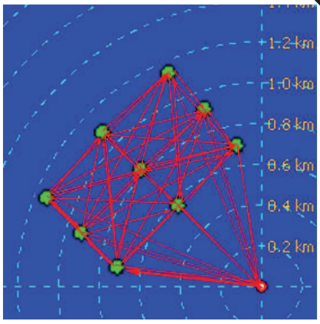
Inter-turbine Interaction

- The interaction between turbines can be modelled using ray tracing techniques
- The incident wave on a specified turbine is traced as it is reflected towards other turbines within the farm
- A threshold value can be defined by the user to set the minimum level for a signal to be traced through the farm
- Using the azimuth angle of the specified turbine and the (traced) path length, the location of the returned signal is placed on the display
- Some "prioritizing" algorithms might be used to increase efficiency



A simplified example of modelling the multiple reflections within a wind farm through tracing the radar signal as it bounces successfully between turbines

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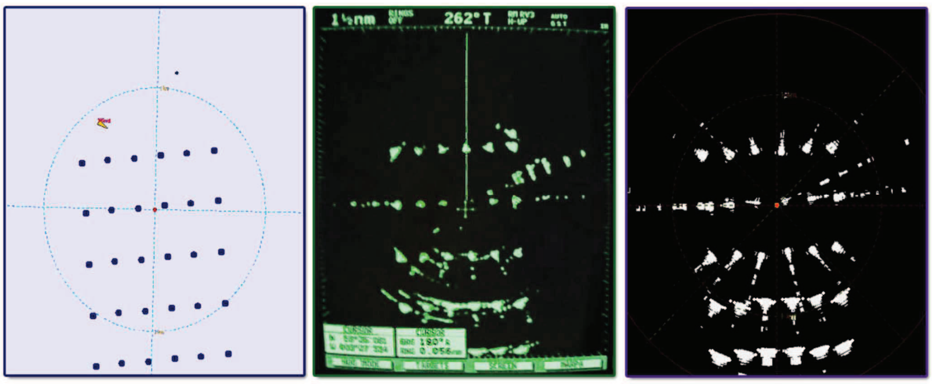
Wind farm impact modelling



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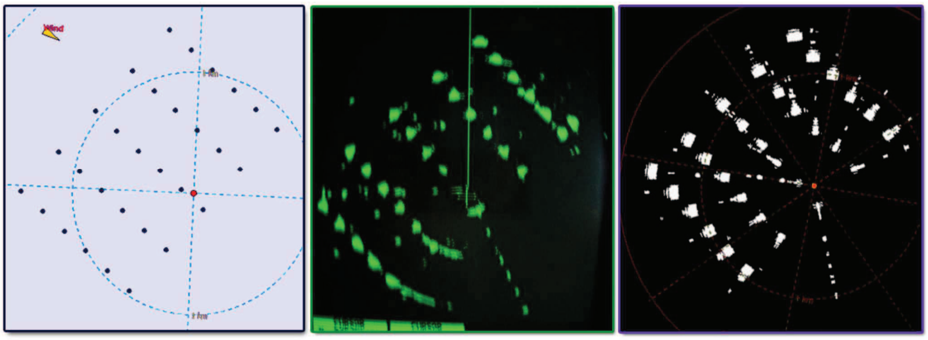
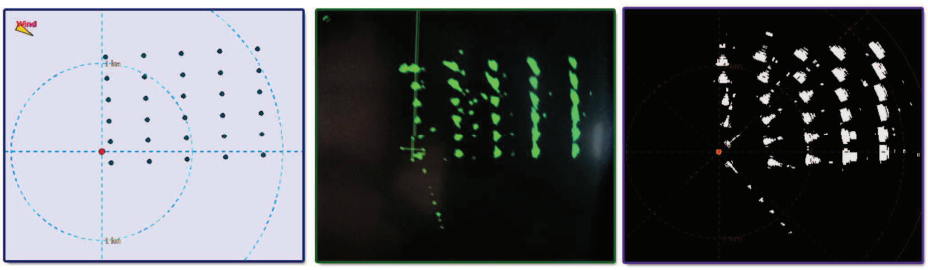
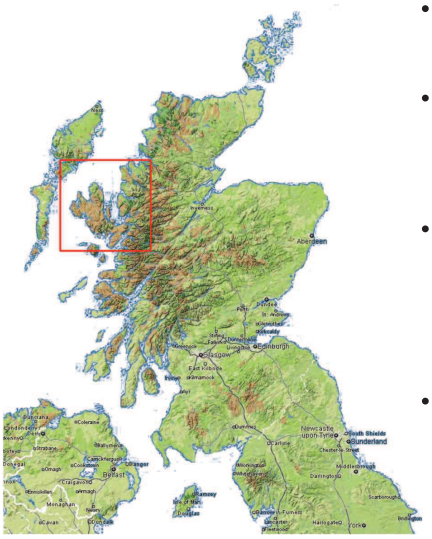
Wind farm impact modelling



Wind farm impact modelling



Wind Farm and Radar Example



- It is known that the wind farm impact on a radar system is site dependant
- Terrain profile of the UK is available at 50m spacing and 1m height accuracy
- Combined with radar models and wind farm/turbine modelling capabilities enables the analysis of site specific issues
- As an example, a 10x10 wind farm is assumed near the west coast of Scotland

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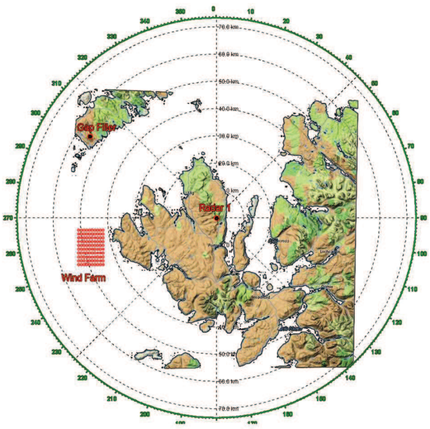
Wind Farm Siting Analysis



- The radar site location and height is identified along with the system specifications
- Specify the location, layout of the proposed wind farm and the turbines size and geometry if available
- Perform radar coverage analysis for the area of interest
- Gap Filling radar location is noted for use in next slides

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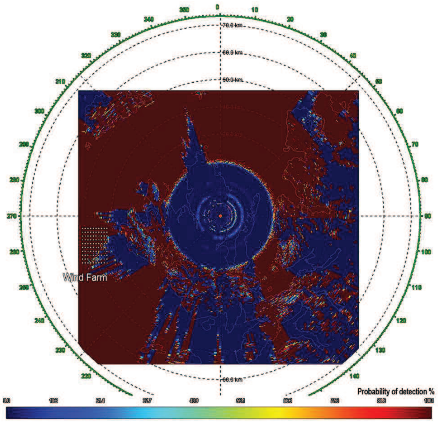
Wind Farm Coverage Analysis



- The radar coverage depends on a number parameters, which include the type and geometry of the turbines used
- The (Exemplar 2MW) blade tip height and radar cross section is used in this modelling scenario
- Coverage diagrams show the area of interest with the probability of the radar detecting the blade tip (at maximum tip height)

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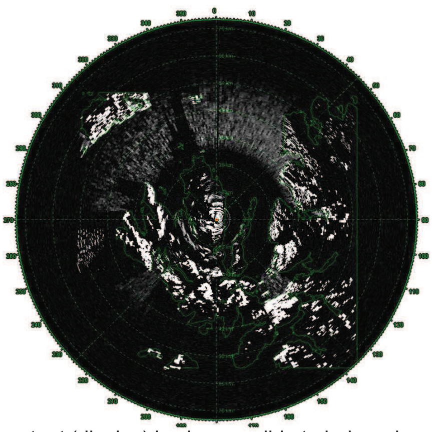
Radar output Analysis



- Modelling of the radar output (display) is also possible to help radar operators and developers understand the possible issues that may arise from a particular wind farm
- This helps to identify the areas of the wind farm that may still produce unwanted radar returns
- Gap filling radars are often suggested as a possible mitigation option

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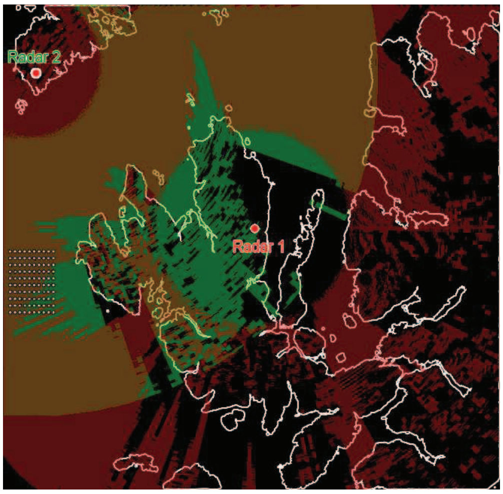
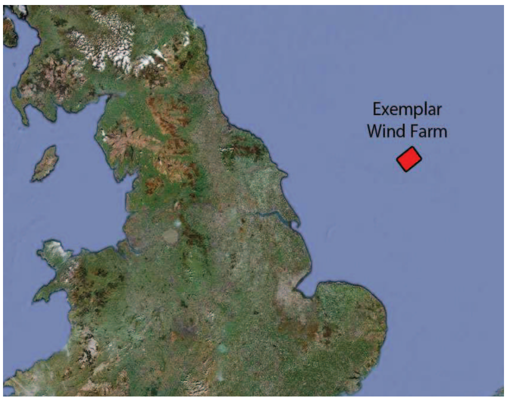
Study of Gap Filling (Netted) Radars



The Exemplar Wind Farm

- Round 3 wind farm
- Total Capacity: 1.28 GW
- Total estate area : 200,000 km^2
- Number of turbines: 256
- Turbine type : Exemplar 5MW
- Rotor Diameter (D): 126m
- Turbine Spacing: 6D x 8D



Modelling the impact of wind farms on nearby oil and gas platforms with radar

- Round 3 wind farms in the North Sea may be located near existing O&G platforms
- O&G platforms might be equipped with radar systems for monitoring nearby traffic and for early collision warning
- Such radar systems might be affected by the installation of wind farms close to the platform due to the large turbine returns and shadowing
- This may cause the loss of existing tracks –and in some reported cases the generation of false tracks

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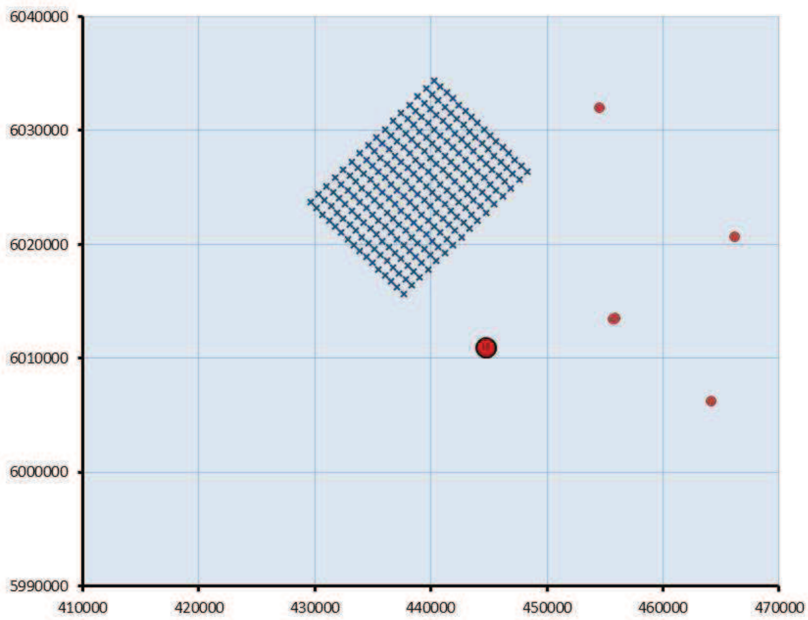
The Exemplar Wind Farm



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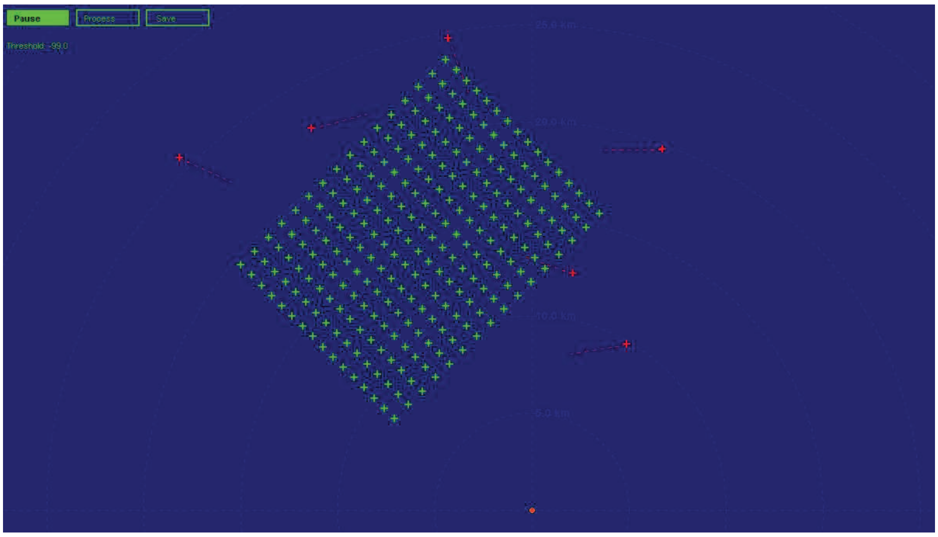
Wind Farm Returns Modelling



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Wind farm and shipping routes

- When an offshore wind farm is installed the shipping lanes may be altered to move around the wind farm
- Redirecting traffic may cause vessels on the shipping lanes to appear as if they are on a collision trajectory with the O&G platform
- This may trigger collision alarms

- Alarms are triggered if:
- The vessel is within a defined radius from the platform
- If the vessel's current speed and direction is heading towards the platform and may collide within a specified time limit

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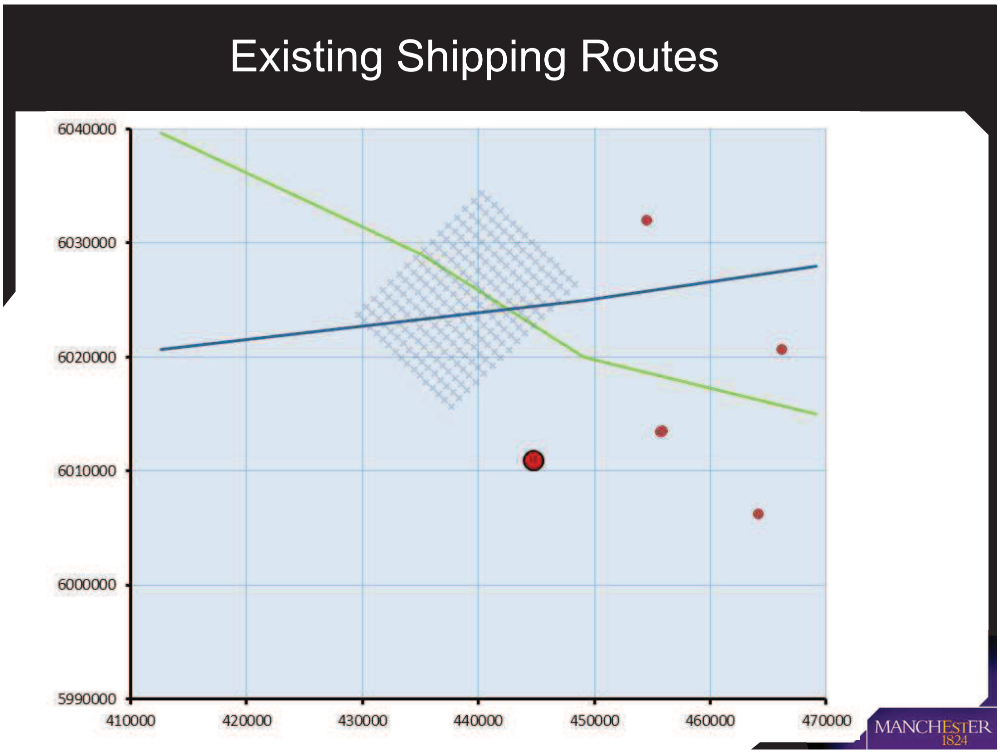
Existing Shipping Routes
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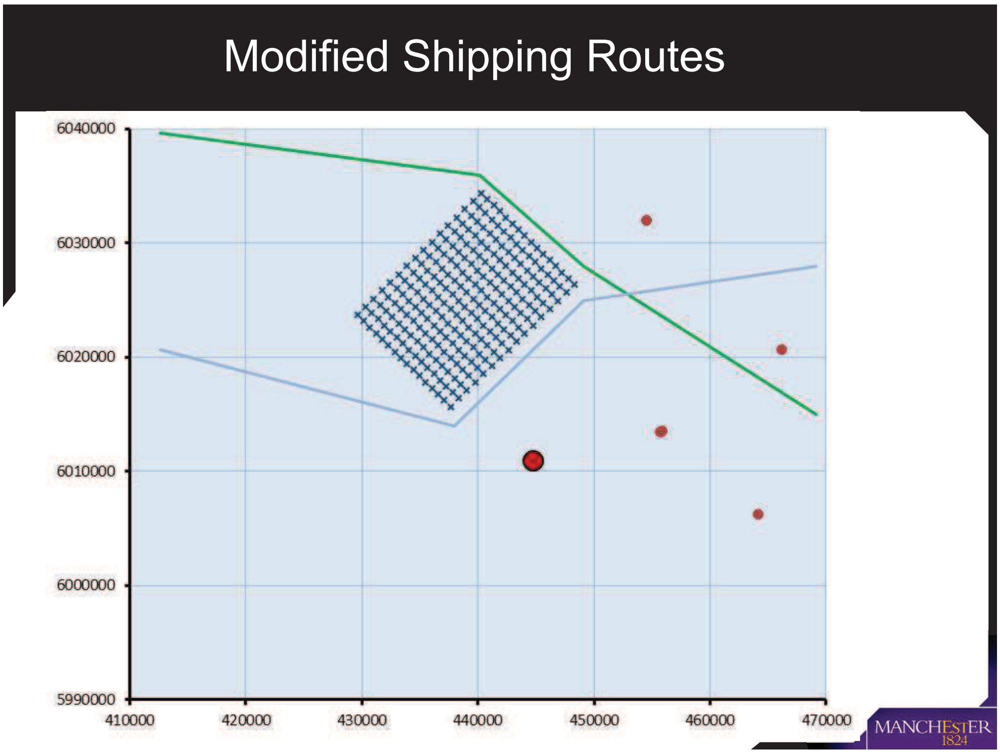
Modified Shipping Routes
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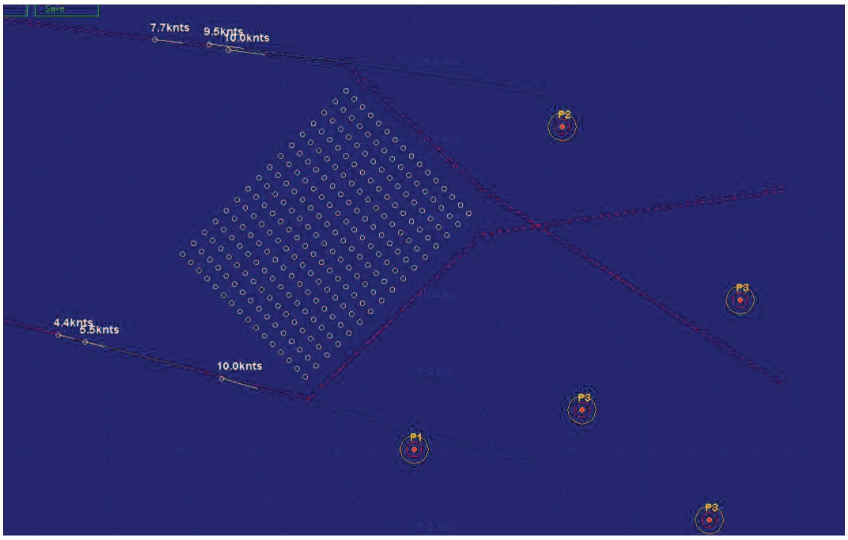

Wind Farm and Radar – Site specific modelling

Passive Radar Based Control of Wind Turbine Collision Warning for Air Traffic PARASOL PARASOL

Jörg Heckenbach, Heiner Kuschel, Jochen Schell, Martin Ummenhofer
Fraunhofer Institut für Hochfrequenzphysik und Radartechnik

Passive Radar based switching of object illumination for air traffic on demand

Gefördert durch:
Bundesministerium für Wirtschaft und Energie
aufgrund eines Beschlusses des Deutschen Bundestages

Förderkennzeichen (FKZ) 0325445

Parasol

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Collision warning illumination in windfarms at night

- blinking lights at night bother citizens
- collision warning lights at night attrackt birds
- in 90% of time no flight activity

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Solution approach: Switching of lights on demand

- Detektions of aircraft in the keep-out area of wind farms (4.5 km) with passive radar sensors distributed in the wind farm
  (Use of DVB-T, DAB+)
- netting of sensors to measure target location, velocity and height
- Generation of a switch signal when:
  - the detektion of a relevant target (height range, distance)
  - shut off of a transmitter
  - error signal during self check

  occurs
- activating of the collision warning illumination when a switch signal is present
- deactivating the illumination when the switch signal is off.

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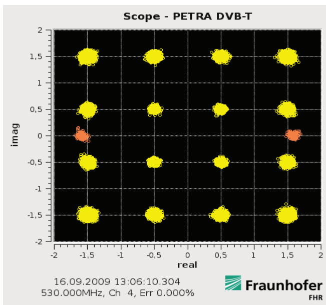
Processing

- 3 sensors locked on GPS for synchronization
- receive DVB-T signals and echoes (450-850 MHz)
- use pilot carriers to measure the channel transfer function and reconstruct the DVB-T signal
- cross-correlate the echoes with a clean reference
  - remove the guard interval
  - cross-correlate symbol by symbol
  - integrate using an FFT of appropriate length
- intersect TDOA ellipsoids of 3 sensors to locate targets



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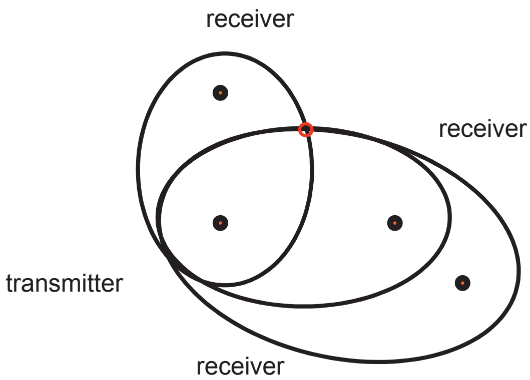
Passive Radar target localisation

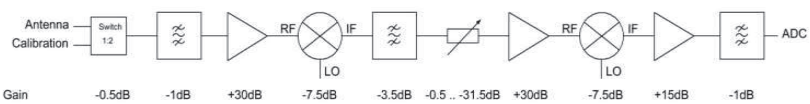
Radar without own emissions

Use of DVB-T or DAB+



Multi-Sensor-Procedure

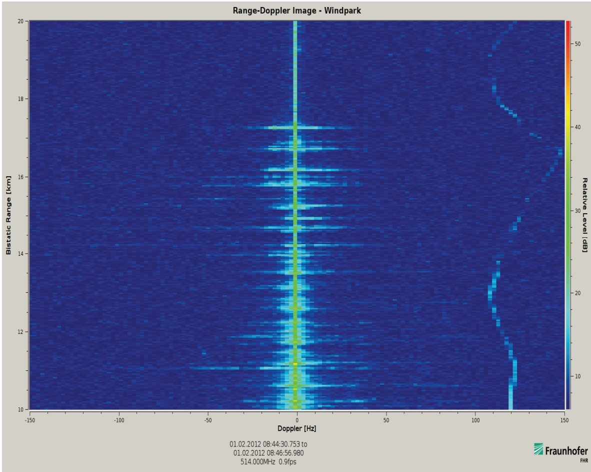
PARASOL sensor (2 elevation channels per sensor)



1st: IF 1105 MHz 2nd IF: 80 MHz

- Using two mixer stages to avoid the back-folding of subjacent channels into the desired measurement channels.
- Sample rate : 64 MSPS
- Sub-sampling in the 3rd Nyquist band eliminates unwanted coupling of power-supply noise into the signal path (usually limited from DC to 5 MHz)

Measurement results of a sensor



Range/Doppler matrix with wind turbine echoes and air target

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PARASOL sensor

- post procesing imlemented on high performance server module
- module provides a 40 GBit/s Infiniband networking interface for high-speed communication
- RAID-0 HDD array enables the continuous storage of data up to 300 MByte/s
- discone antennas to cover a large width
- two vertically stacked antennas to allow height measurement
- radar absorbing material on backplane to avoid reflections from mast
- Plexi radome for weather protection

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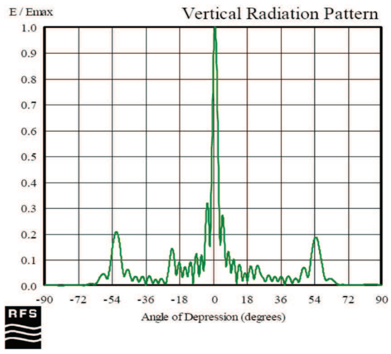
Distribution optimization of sensors

Constraints to be considered

- Transmitter antenna characteristics
  - narrow elevation beam 3°-5°
  - tilt towards horizon 1°
- all sensors should have about the same coverage
- shielding by the wind power pylons
- bi-static target radar cross section



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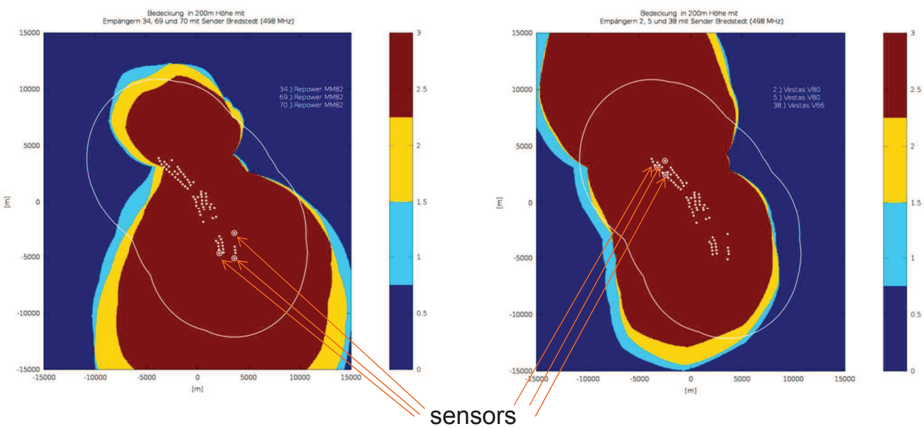
Coverage of sensors in wind farm with TX1



sensors

coverage of southern part

coverage of northern part

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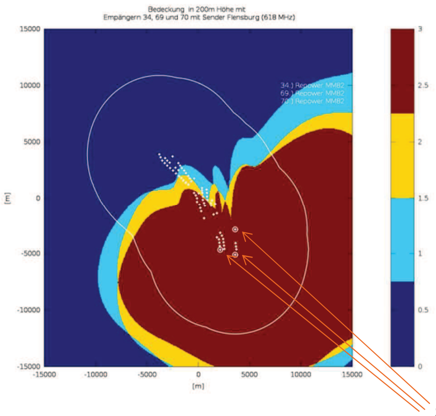
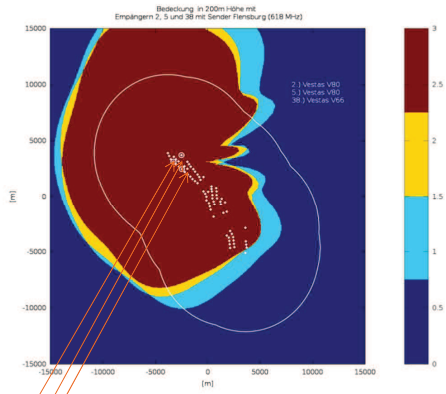
Coverage of sensors in wind farm with TX2





sensors

coverage of southern part

coverage of northern part

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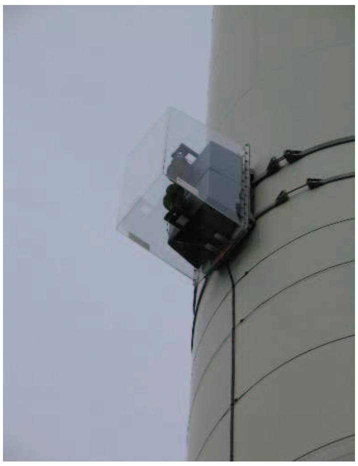
Installation in wind farm Reußenköge

In Oktober 2013 three sensors of the PARASOL system were installed in the wind farm Reußenköge in northern Germany. Each sensor consists of the receiver / server module and the antenna . The receiver / server modules were installed in the tower of respective wind turbines



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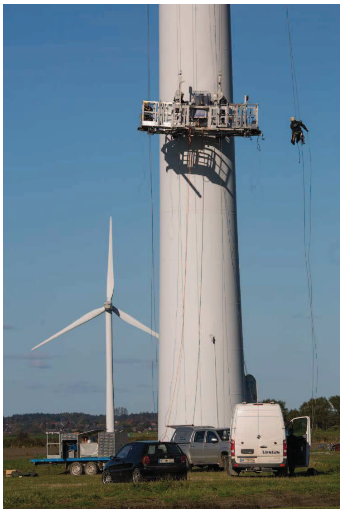
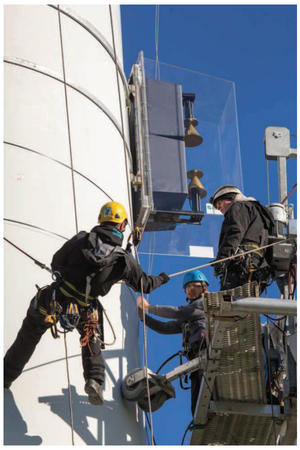
Mounting of the antennas

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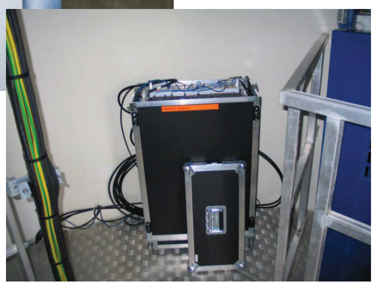
Mounting of the systems





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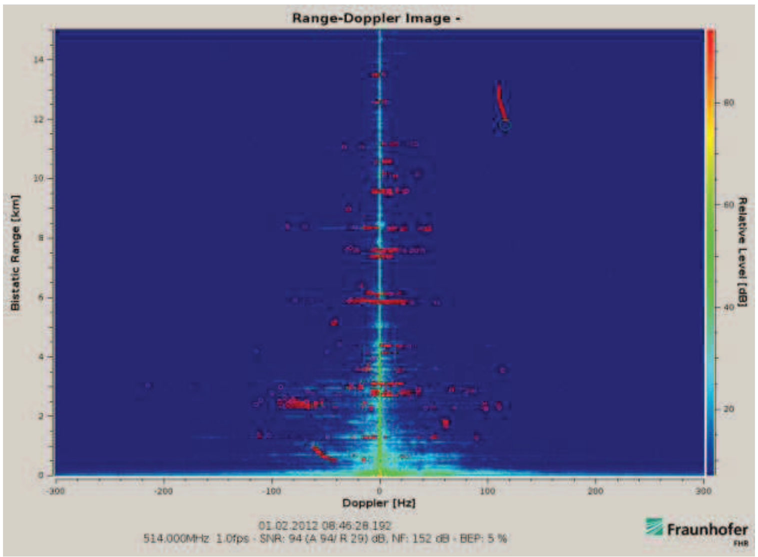
Target track and wind turbine plots in *Reußenköge*



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Conclusions

- PARASOL is a „green" sensor system
- it exploits DAB+, DVB-T and possibly LTE
- nightly light pollution is reduced

Advantages

- no frequency allocation required
- no additional electro-magnetic emissions
- less costly than active radar (no own transmitter)
- 3 sensors per wind farm can be sufficient
- 360° coverage, no „Cone of Silence"
- DVB-T (DAB+) are fully available
- no weather constraints

Challenges

- Object classification (bird swarms, small aircraft, ground vehicles)
- measurement of object height
- optimum sensor distribution

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Additional aspekts of PARASOL

- passive radar network PARASOL can fill gaps in air surveillance caused by wind turbine interference
- passive radar network PARASOL can be used to monitor the „health“ condition of wind turbines by micro-Doppler analysis

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ONERA
THE FRENCH AEROSPACE LAB
return on innovation
www.onera.fr

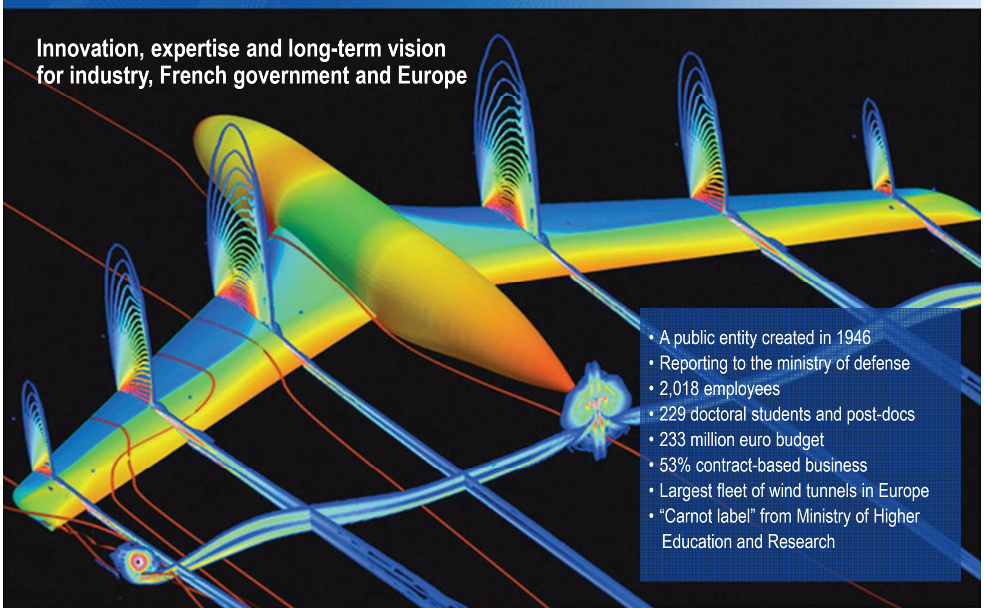

Mastery of radar signatures of wind turbine and their impact on radars
jean-paul.marcellin@onera.fr
ONERA
THE FRENCH AEROSPACE LAB
return on innovation

Summary

- Introduction
  - Short presentation of ONERA
  - Role of ONERA on the topic " impacts of wind farms on radars"
- Main activities
  - Experimental
  - Simulation
  - Expertise
- Field of interest

3

The French Aerospace Lab



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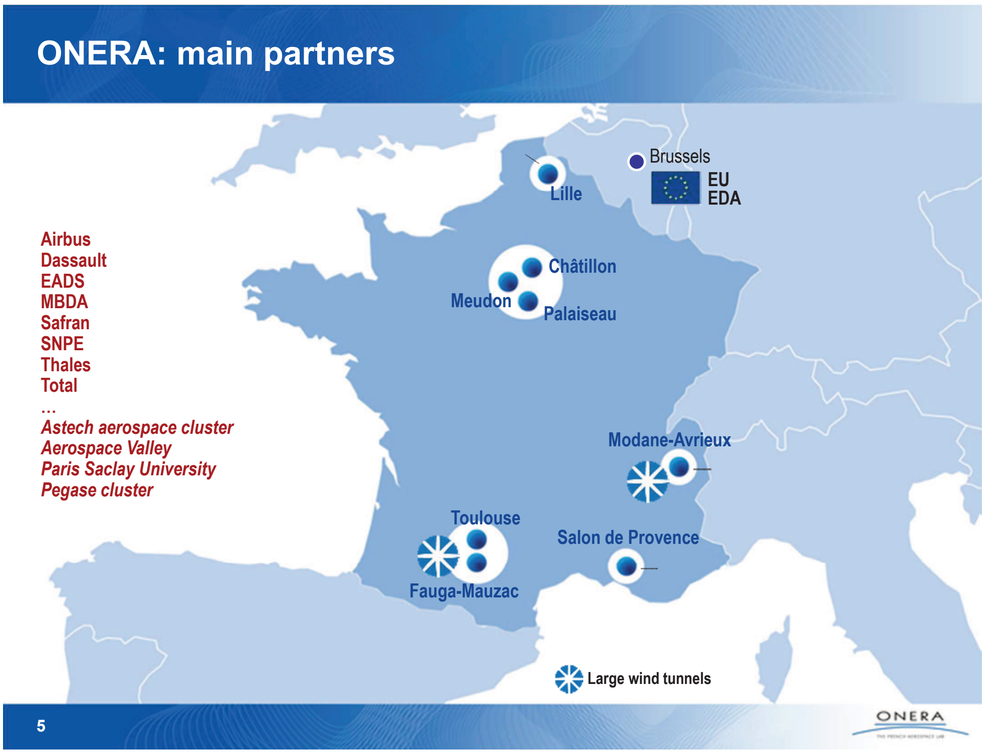
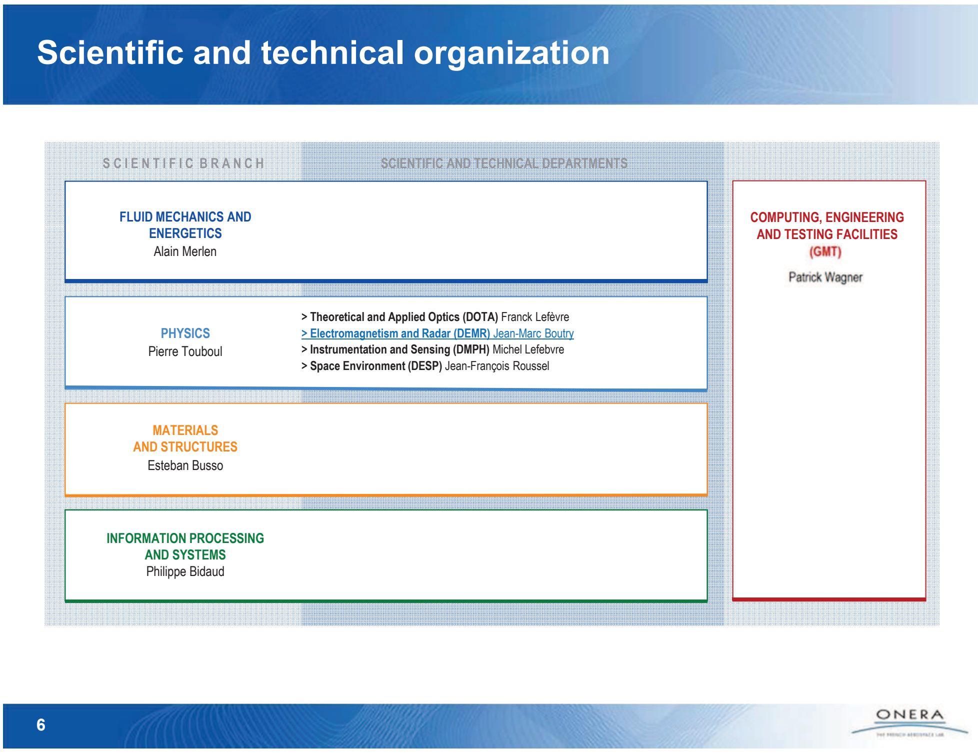

ONERA: main partners
Airbus
Dassault
EADS
MBDA
Safran
SNPE
Thales
Total
...
Astech aerospace cluster
Aerospace Valley
Paris Saclay University
Pegase cluster
Brussels
EU
EDA
Lille
Châtillon
Meudon
Palaiseau
Modane-Avrieux
Toulouse
Salon de Provence
Fauga-Mauzac
Large wind tunnels
5
ONERA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FLUID MECHANICS AND ENERGETICS
Alain Merlen
PHYSICS
Pierre Touboul
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Philippe Bidaud
COMPUTING, ENGINEERING AND TESTING FACILITIES (GMT)
Patrick Wagner
6
ONERA

Electromagnetism and Radar department

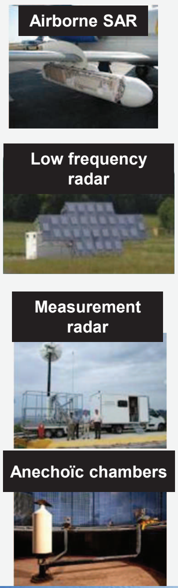
Research and study programs in electromagnetism, microvawes and radar

Activities for MOD, security, aerospace, environment

Large park of experimental resources (ground / airborne radars, anéchoïc Chambers

expert for DGA on Radar Environment

140 engineers, PhD and technicians



Propagation

Antennas

Radar processing

Electronic warfare

EMC

Radar signatures stealth techniques

7 ONERA

Interaction Radar ↔ wind farms French context and role of ONERA

- Planning permission for wind farms are subject to the opinion of radar operators
- Many projects are blocked → conflict !

ONERA is involved on this topic as an expert for the state agencies and scientific and technical support for industry

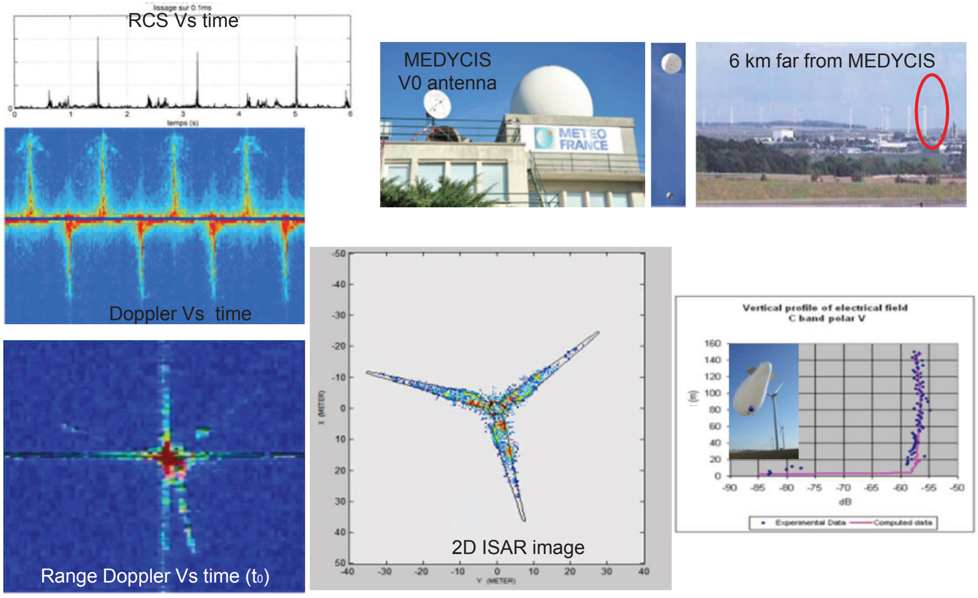
→ program « SiPRÉ » sponsor ADEME
Radar signature analysis of a wind turbine;
First approach to develop a simulation tool of the impact on Meteorological radars

→ program « EODIS » (ONERA + AIRBUS DS) sponsor ADEME
First demonstator of stealth blade

→ Program « DEMPERE » (ONERA, Thales TR6, OKTAL-SE) sponsor DGA: MoD
Simulation tool of radar impact of a wind farm on military radars

8 ONERA

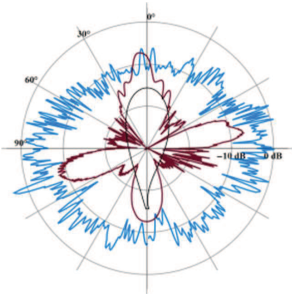
Radar signature analysis of a wind turbine
First experimental results from MEDYCIS V0

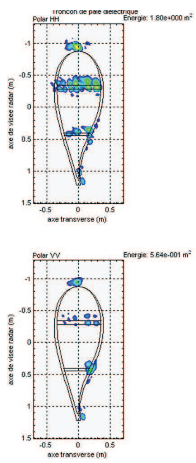


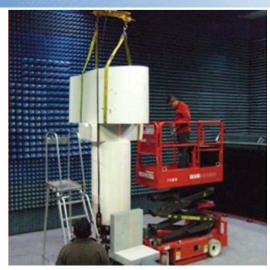
Example of Radar signature of a blade section

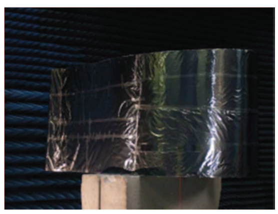
Some echoes located inside the blade
Depends on
- **materials used,**
- **shapes (internal/external),**
- **manufacturing process**

skin of blade may boost
- **surface propagation effect**
- **wave guide propagation effects**

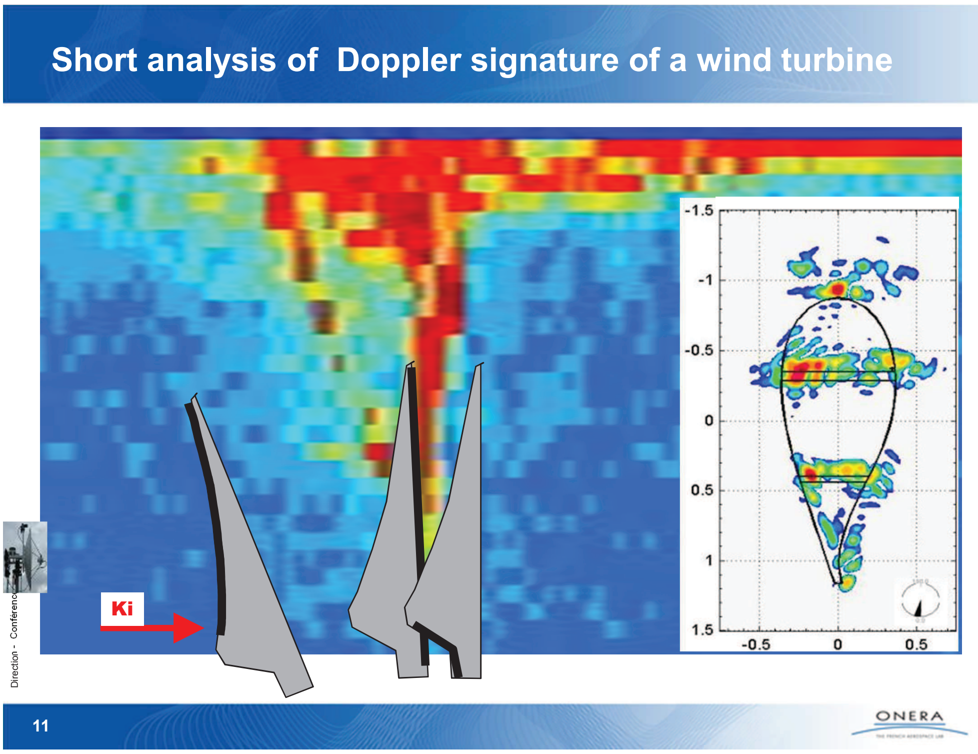


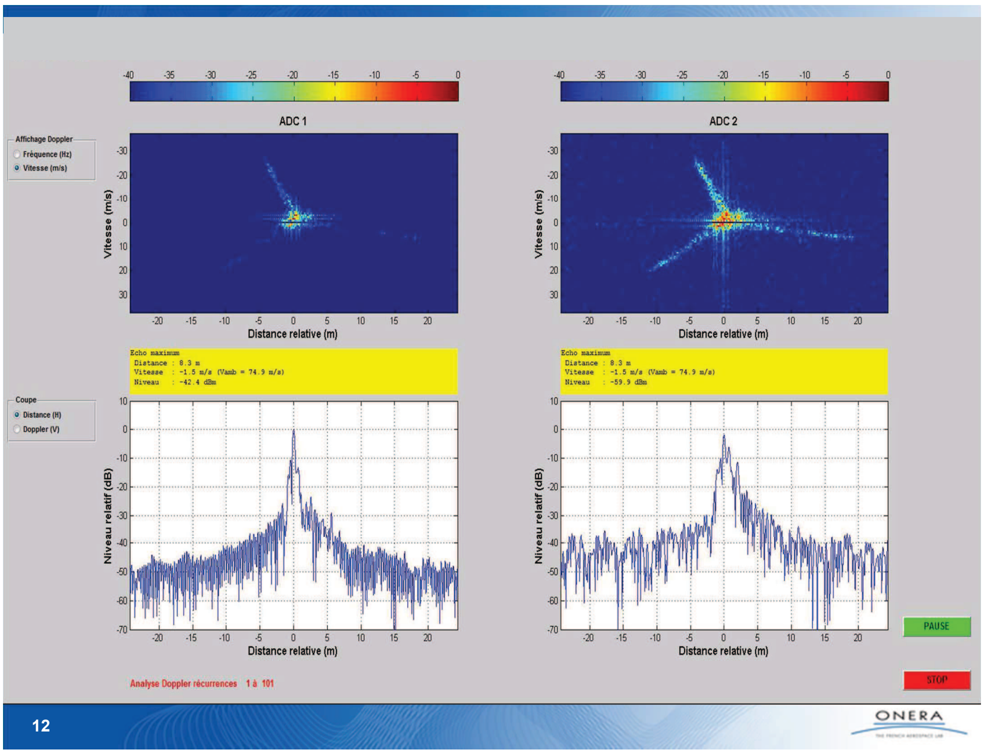






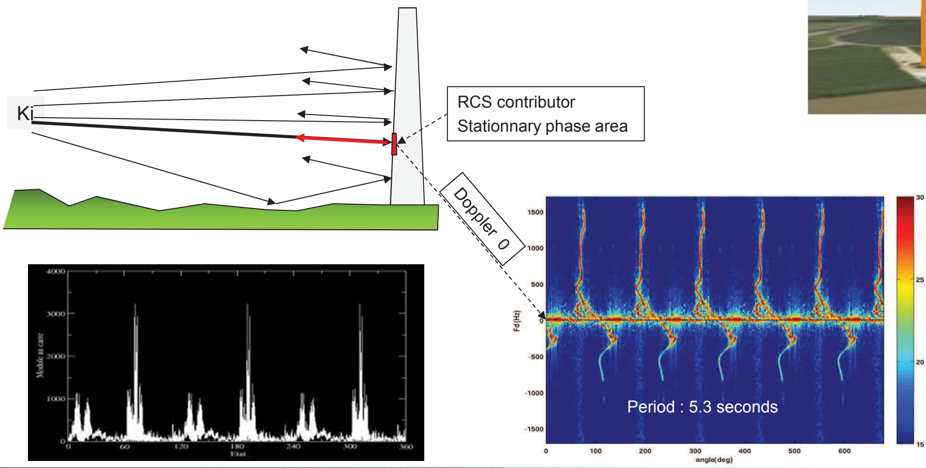
Direction - Conférence


Short analysis of Doppler signature of a wind turbine
Ki
-1.5
-1
-0.5
0
0.5
1
1.5
-0.5
0
0.5
11
ONERA


ADC 1
ADC 2
Vitesse (m/s)
Distance relative (m)
Niveau relatif (dB)
PAUSE
STOP
12
ONERA

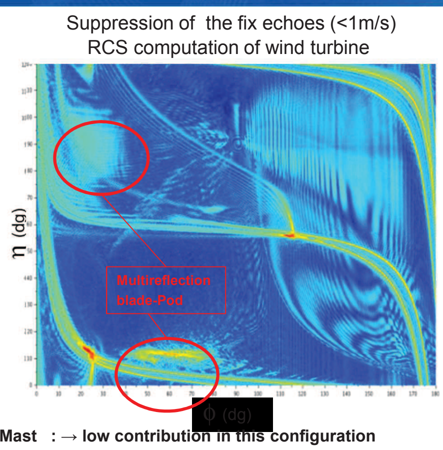
Computation of Doppler signature of a wind turbine on a ground surface

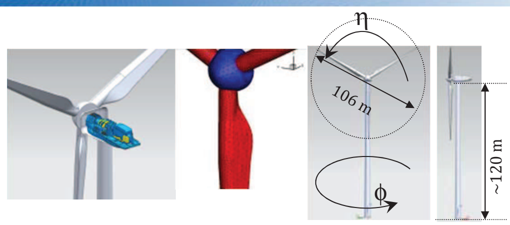
OKTAL-SE-RAY-EM software
Metallic wind turbine on DTM (BD Alti of IGN (resol 25m) + land cover (Corine)
C band, spherical front phase surface , 5600m far from transmitter, →near field
Antenna pattern: isotropic in a solid angle (apex angle 10 dg) → wind turbine whole illuminated



13 ONERA

RCS computation of a wind turbine (S band, generic shape)



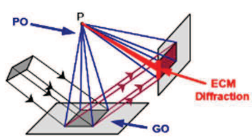


Mast : → low contribution in this configuration
(conical shape + near field effect)
Pod : → High contribution when perpendicular
to range axis + coupling effects with blades
Blade : → Doppler signature , flashes,
coupling effects with fix structure

Reflexion from clutter and distorsion on blades are neglected

OKTAL-SE – ONERA Collaboration
software SE-RAY-EM

- Ray Tracing + asymptotic high frequency electromagnetic methods (Geometrical Optics, Physical Optics and Method of Equivalent Currents)
- GO interactions except last interaction PO
- Multireflections
- Monostatic and multistatic configurations



14 ONERA

EODIS : Demonstrator of stealth blade, RAM efficiency

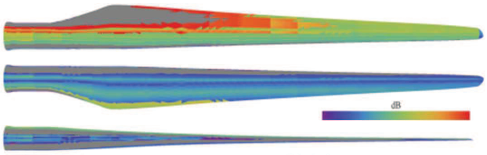
Program EODIS ONERA + AIRBUS DS

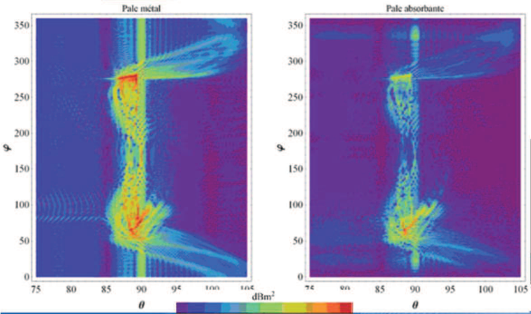
- Measurement of local reflexion coefficients (reference metal)
  High range resolution (suppression of ground echoes)
- Projection of reflexion coefficients on cells of the CAD model
- RCS computation

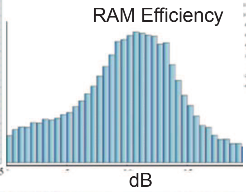
Lower surface

Upper surface

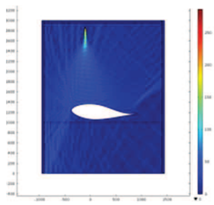
Leading edge







Electrical field
in vertical section



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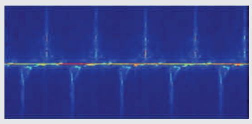
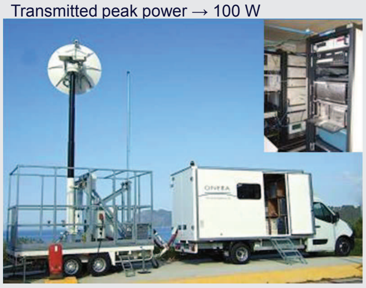
DEMPERE : Experimental validation

- Comparison between
  - Final outputs of simulator DEMPERE and outputs of operational radars (falses echoes , detection of targets behind a wind farm),
  - Intermediate outputs (EM data) and results of specific experimentations, using MEDYCIS V1

MEDYCIS V1: Technical characteristics

- Lightweight plateform, standalone
- S & C band (2.8 →3.2 GHz ; 5.45 → 5.85 GHz)
- H and V polarization
- antenna Axis→ 7 m
- Reference target: sphere under captive balloon or UAV
- Transmitted peak power → 100 W





Arbitrary wave generator

- Continuous waveform, chirp, codes,…
- From 2, up to 6 GHz

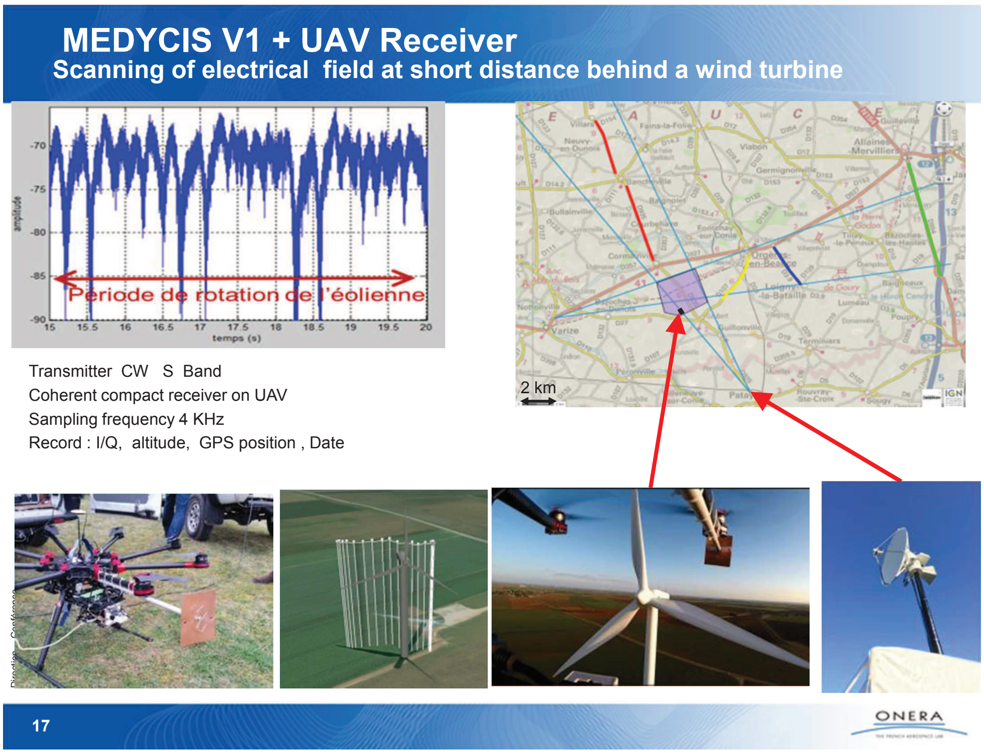
Tranmission/ réception chain

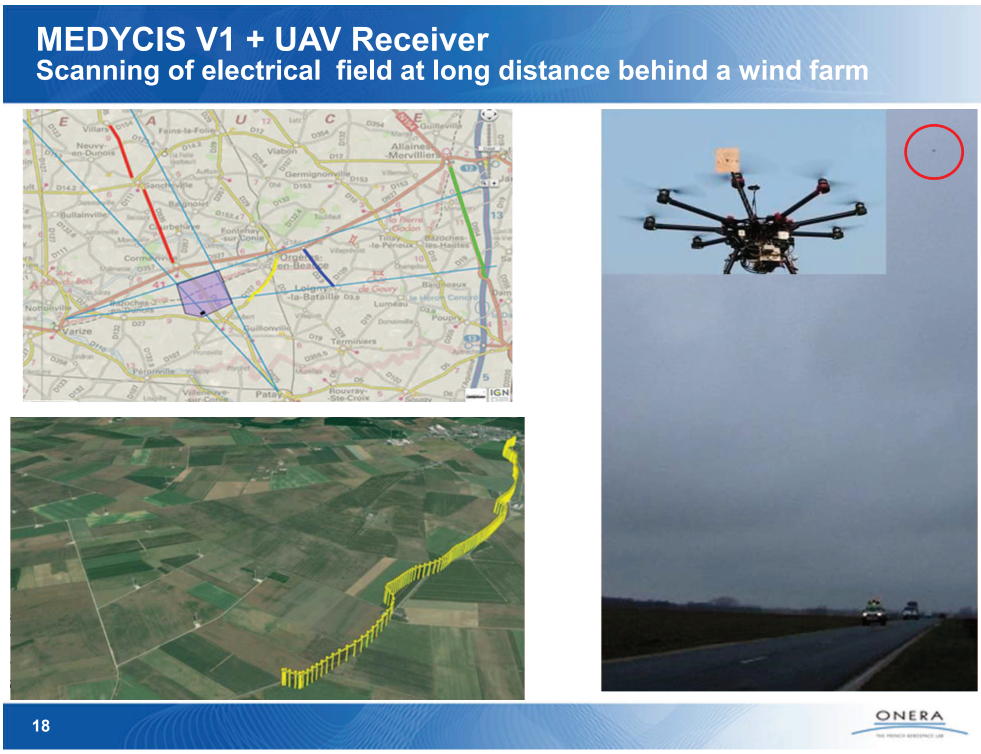
- Frequency bandwidth → 400 MHz (range resolution< 0,5m)
- frequency sampling → >10^9 Hz
- Digitization 12 bits

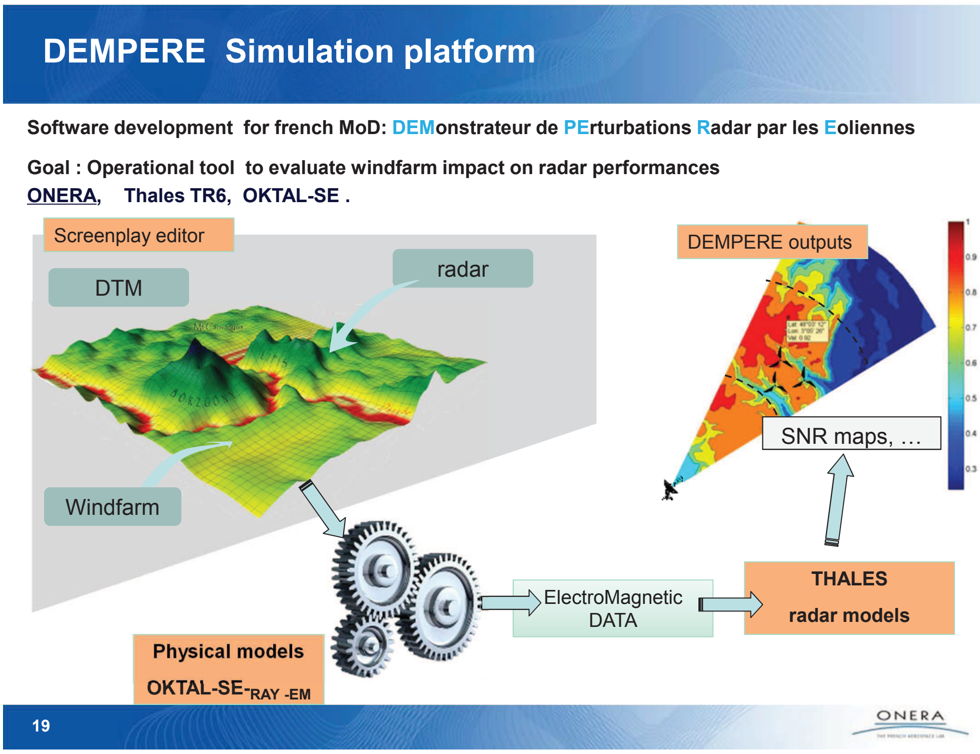
Measurement

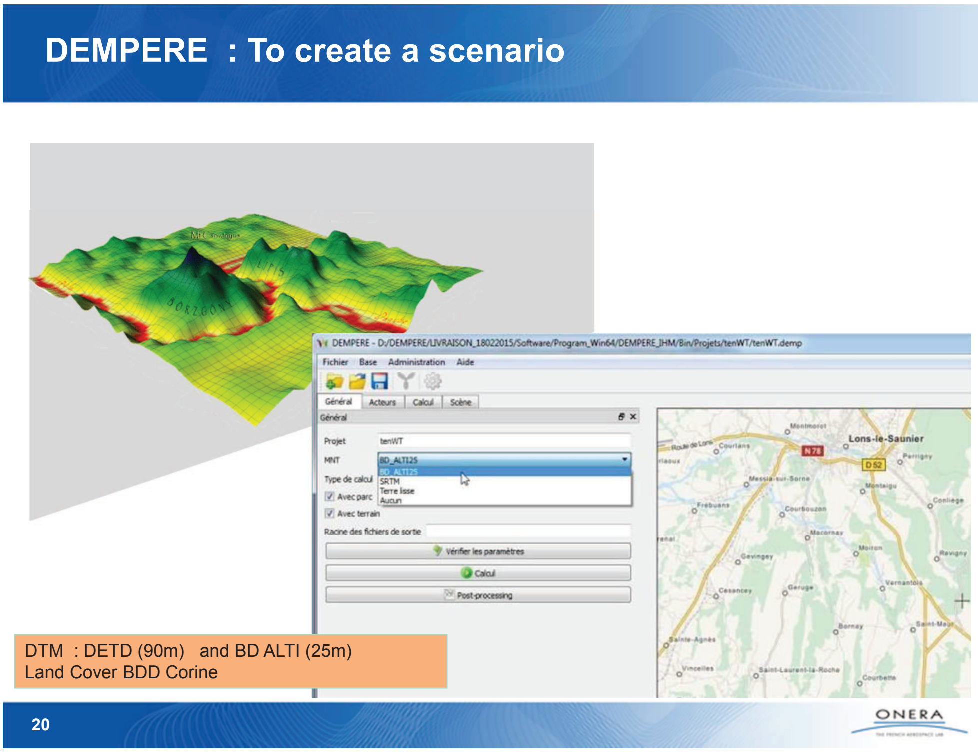
- Dynamic RCS versus time of fix deformable targets
- Radar environment (sea clutter, …)

16

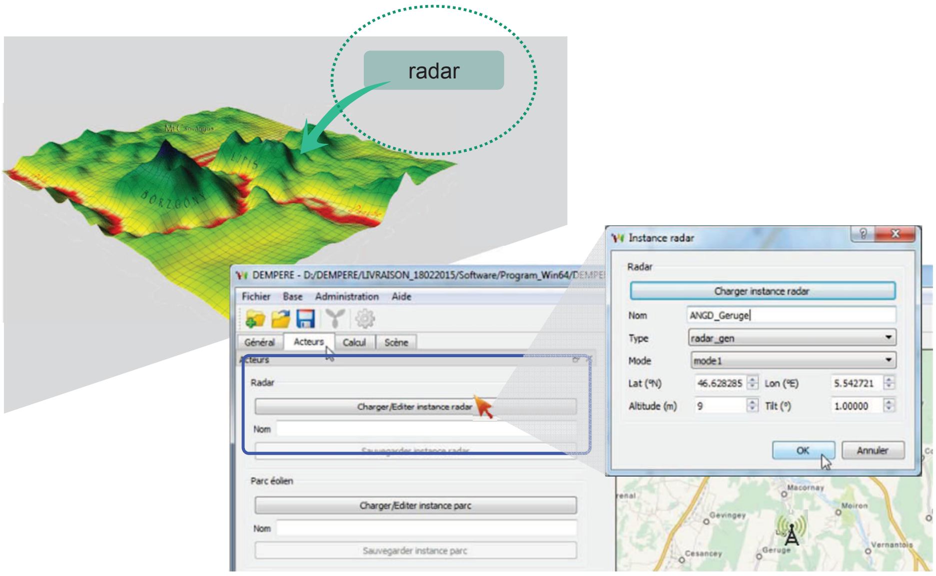

MEDYCIS V1 + UAV Receiver
Scanning of electrical field at short distance behind a wind turbine
Période de rotation de l'éolienne
amplitude
temps (s)
Transmitter CW S Band
Coherent compact receiver on UAV
Sampling frequency 4 KHz
Record : I/Q, altitude, GPS position , Date
2 km
17
ONERA


MEDYCIS V1 + UAV Receiver
Scanning of electrical field at long distance behind a wind farm
18
ONERA


DEMPERE Simulation platform
Software development for french MoD: DEMonstrateur de PErturbations Radar par les Eoliennes
Goal : Operational tool to evaluate windfarm impact on radar performances
ONERA, Thales TR6, OKTAL-SE .
Screenplay editor
DTM
radar
Windfarm
DEMPERE outputs
SNR maps, …
ElectroMagnetic DATA
THALES radar models
Physical models
OKTAL-SE-RAY -EM
19
ONERA

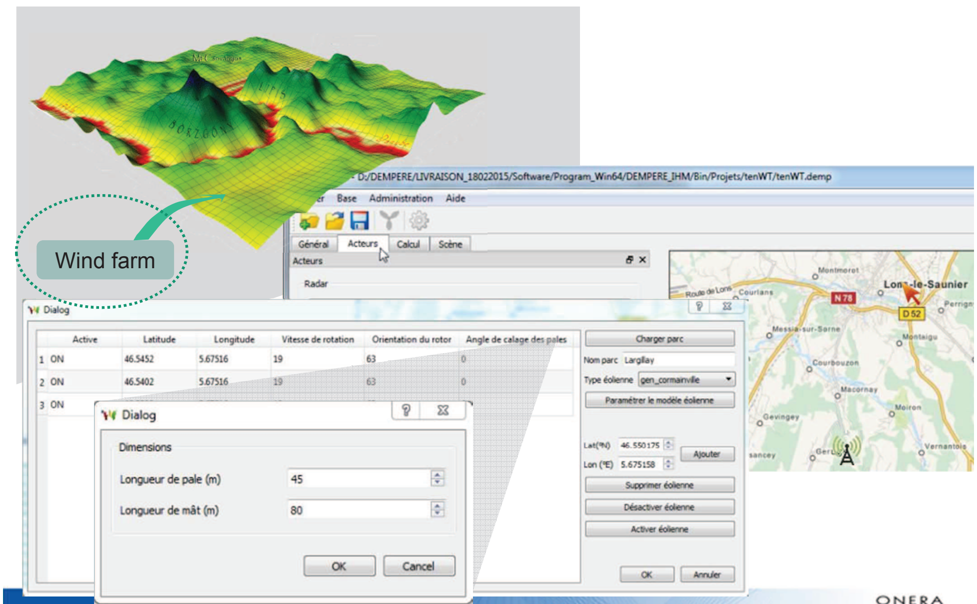

DEMPERE : To create a scenario
DTM : DETD (90m) and BD ALTI (25m)
Land Cover BDD Corine
20
ONERA

DEMPERE: to create a radar



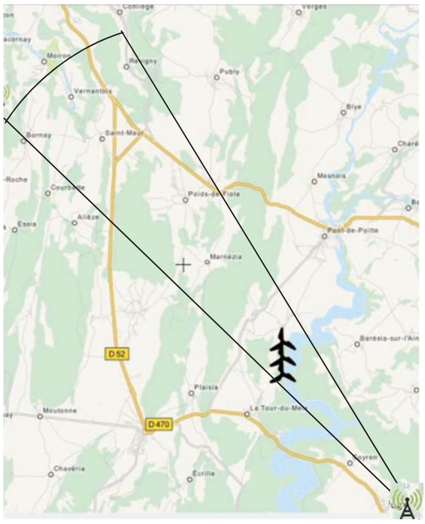
21

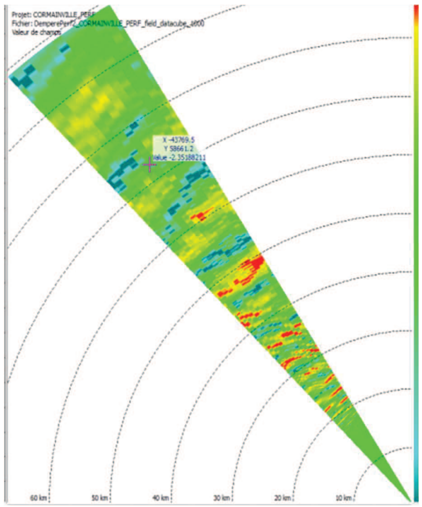
DEMPERE: to create a wind farm



22

DEMPERE: a example of final output



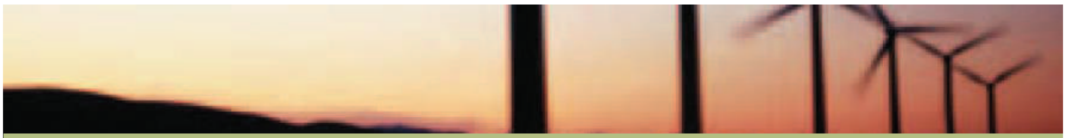


23

ONERA

24

ONERA



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Let's work together

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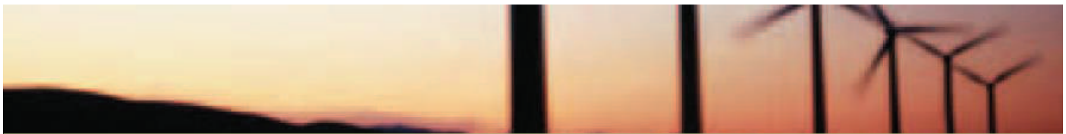

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October 2015

Radar Solutions – Proven and Promised

Kai Frolic

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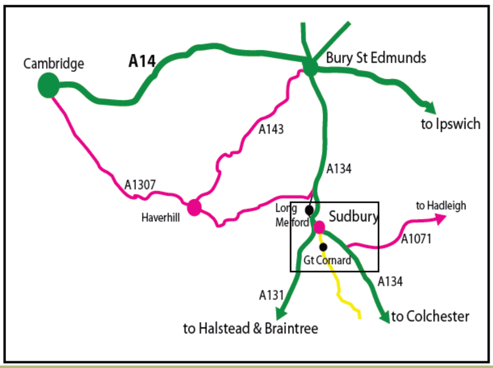
Introduction

- Market town of Sudbury
- Essex / Suffolk border
- East Anglia, England, UK



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Introduction

- Wind turbines and radar
- Navigation aids
- Physical Safeguarding
- Wireless communication systems
- Solar photovoltaics
- Mitigation solutions

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Introduction

- Projects in:

- UK
- Ireland
- Netherlands
- Belgium
- France
- Sweden
- Finland
- Cyprus
- Bulgaria
- Oman
- Jordan
- South Africa

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Background – Radar Types

- Primary Surveillance Radar (PSR)
  - Echo and response
  - Non-cooperative
- Secondary Surveillance Radar (SSR)
  - Interrogation and response
  - Cooperative
- Precision Approach Radar (PAR)
  - Military
  - Used for final approach only
- Other
  - VTS
  - Marine
  - Meteorological
  - Even more!




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Background – Wind Turbine Interference

- Radar clutter

- Turbines shown on radar screen as a target
- Affects primary surveillance radar
- Can cause distraction
- Can cause unnecessary avoiding action

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Background – Wind Turbine Interference

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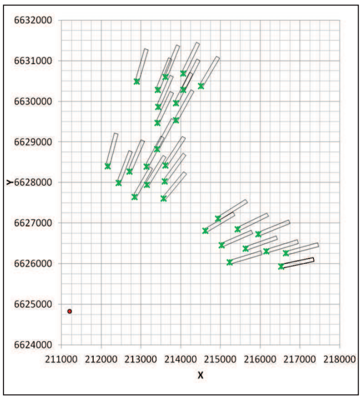
Background – Wind Turbine Interference

- Shadowing
  - Radar signal weakened by the turbines
  - Affects PSR and SSR
  - Targets become less detectable
- Multipath effects
  - Radar signal is reflected via the wind turbine between the aircraft and the radar
  - Affects PSR and SSR
  - False targets and bearing errors
- Desensitization
  - Large amount of energy reflected by turbines
  - Small targets become less detectable



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Types of Mitigation

- Technical mitigation
  - New / modified hardware
  - New / upgraded software
  - Adjustments to the wind farm
- Operational mitigation
  - Managing / tolerating the impact
  - Ensuring information is distributed
  - Updating relevant databases and maps

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Proven Mitigation – Overview

- Numerous solutions are delivering already
- Radar Blanking
- Radar in-fill
- Non-Automatic Initiation Zone
- New / additional radar
- Radar configuration
- Wind farm design
- Operational

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Proven Mitigation – Radar Blanking

- Solution for PSR interference
- Returns from affected area are suppressed
- Removes turbine clutter but also removes real aeroplanes from display
- Used by:
  - NATS for En-Route radar in the UK (e.g. Claxby)
  - Civil airports – e.g. Newcastle
- Not popular for military radar

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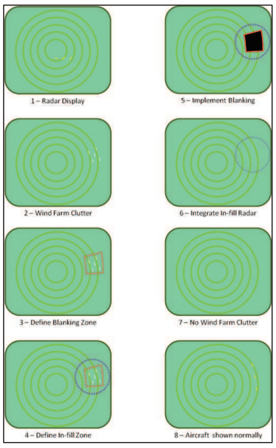
Proven Mitigation – Radar In-Fill

- Solution for PSR interference
- Returns from affected area are suppressed
- Coverage in blanked area
- Used by:
  - NATS for En-Route radar in the UK (e.g. Lowther Hill)
  - Civil airports – e.g. Glasgow, Doncaster Sheffield



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Proven Mitigation – Non-Automatic Initiation Zone

- Solution for PSR interference
- A zone is defined around the wind farm
- Aircraft tracks that are initiated within the zone are ignored
- Tracks that initiate outside the zone continue to be displayed

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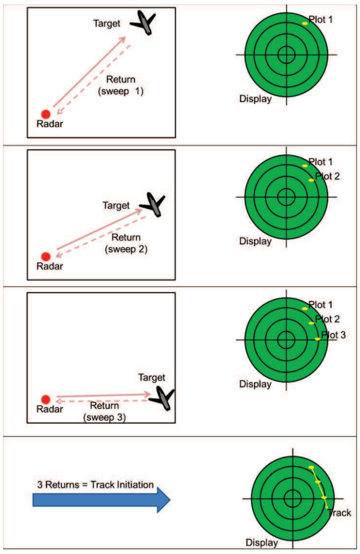
Proven Mitigation – Non-Automatic Initiation Zone



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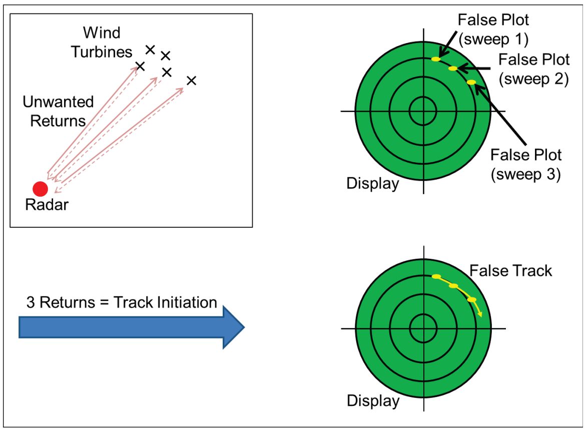
Proven Mitigation – Non-Automatic Initiation Zone



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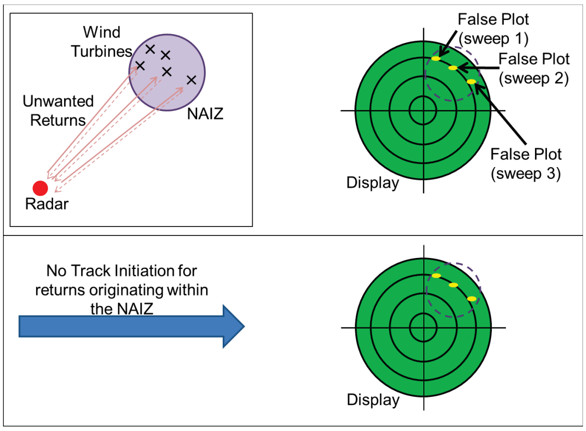
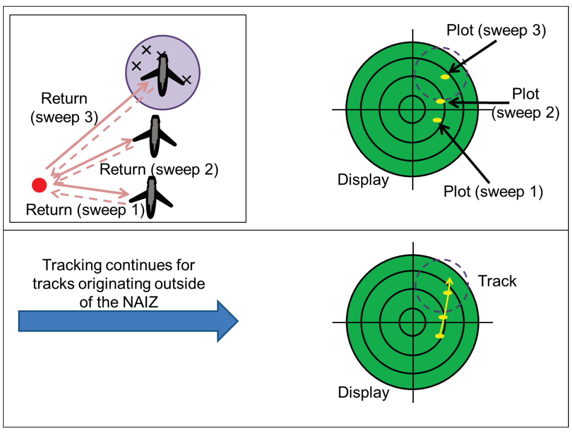
Proven Mitigation – Non-Automatic Initiation Zone



Proven Mitigation – Non-Automatic Initiation Zone



Proven Mitigation – Non-Automatic Initiation Zone

- Solution for PSR interference
- A zone is defined around the wind farm
- Aircraft tracks that are initiated within the zone are ignored
- Tracks that initiate outside the zone continue to be displayed
- Used by:

- Civil Airports – e.g. Bratislava (Slovakia), Kastrup (Denmark), Southend (UK)
- Military Air Defence Radar in the UK

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Proven Mitigation – New / Additional Radar

- Solution for PSR and SSR interference
- Newer radar can have more mitigation capabilities than older radar
  - Newer PSR can have more blanking / NAIZ / in-fill capability
  - 'Mode-S' SSR are less susceptible to interference than older ones
- Additional radar can provide in-fill coverage
- Used by:
  - Civil Airports – e.g. Glasgow and Doncaster Sheffield (UK)
  - Military Air Defence Radar in the UK – upgraded radar were in part funded by renewable energy developers

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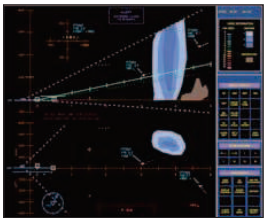
Proven Mitigation – Radar Configuration



- Solution for various radar types
- Interference can be accommodated to a degree by configuring the radar differently
- Unlikely to be applicable in operationally critical areas
- Used by:

- Military PAR (UK) – e.g. RAF Wittering

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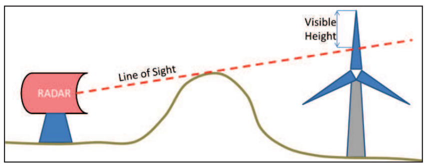
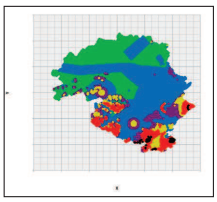
Proven Mitigation – Wind Farm Design





- Solution for any radar type
- Reducing turbine size can hide a wind farm from a radar
- Aligning turbines on a radial can reduce impacts – particularly for SSR
- Use of screening by terrain or obstructions can reduce detectability
- Relocation of turbines outside safeguarding zones – e.g PAR
- Used extensively

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Proven Mitigation – Operational

- Solution for any radar type
- Impacts outside critical areas can be tolerated
- Ensure all relevant parties are notified – ATC, regulators
- Used extensively
  - E.g. Glasgow Prestwick PSR (UK) detects a number of wind farms including Hare Hill, Windy Standard and Ardrossan
  - Many cases of clutter being tolerated

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Promised Mitigation – Overview

- Numerous solutions at various stages of development are often discussed
- Local in-fill
- Radar-proof turbines
- Display configuration (Thruput)
- Project RM
- Airspace changes
- Other options

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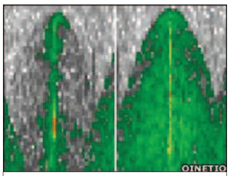
Promised Mitigation – Local In-Fill

- Same principle as 'normal' in-fill
- Uses a bespoke sensor to provide coverage in the gap
- Potentially more versatile and cheaper than using a regular radar
- Many providers
  - Aveillant
  - Terma
  - C-Speed
  - Others
- Various approaches taken by manufacturers
- Spectrum issues

Promised Mitigation – Local In-Fill

- Solutions demonstrated at various trials:
  - US Interagency Field Test and Evaluation trials (Texas, 2013)
  - NATS/Terma trial (2014)
  - Various airport trials (East Midlands, Cambridge and Glasgow in the UK)
- Discussed as a solution over 8 years ago
- Not yet implemented in order to allow construction of a wind farm

Promised Mitigation – Radar-proof Turbine


Source: BBC (2009)

- Stealth technology or Radar Absorbent Material technology
  - Designed to cause destructive interference in the reflected signal

- Turbine geometry modified
  - Designed to reflect signals away from the radar
  - Designed to turn slowly enough to avoid the MTI/MTD

- Solutions demonstrated at trials as early as 2009 (turbine at Swaffham, UK. Radar at RAF Marham, UK)

- Not yet implemented in order to allow construction of a wind farm (aviation)

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Promised Mitigation – Display Configuration (Thruput)

- New hardware installed between radar and display

- Changes to the radar display can make radar clutter less distracting

- Display logic used to dim the colour of the pixels associated with the clutter

- This does mean aircraft tracks passing over these pixels will have gaps

- Solution has been in development for a couple of years

- Reportedly had site acceptance testing signed off at Durham Tees Valley Airport (UK) in 2014

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Promised Mitigation – Project RM

- By tilting the radar beam – mechanically or electroncially – clutter from wind farms can be reduced
- Straightforward tilt reduces low level coverage, which is unpopular with radar operators
- NATS in the UK has worked with Raytheon to develop a solution (Project RM) for wind farms based on internal radar techniques including:

- Comparing the high and low radar beams
- Doppler filtering and signal processing

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Promised Mitigation – Project RM

- Project RM is for en-route radar and only applicable for:

- Turbines over 9 nm from the radar
- Blade tips that subtend a minimum angle relative to the base of required coverage

- Project RM has been in development for a number of years
- It is now actively being offered by NATS in the UK for particular radar subject to siting rules

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Promised Mitigation – Airspace Changes

- Significance of clutter depends on airspace
- Establishing controlled airspace around an area of clutter could reduce the impact of interference
- This has been discussed for long time but is not been taken forward as a solution for a wind farm in practice

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Promised Mitigation – Other Options

- Other options talked about include:

- Cyrrus Smartener – combines information from multiple radar to determine whether clutter is due to wind turbines
- Fitting turbines with transponders
- Alternative surveillance systems – give up on radar all together

- These options have not been realised in practice to date

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Solutions that deliver

- The solutions taken forward in practice are often old and crude
- More sophisticated options have been identified, developed and trialled
- Why have so few MW have been released by newer solutions?

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Obstacles for New Mitigation

- Who bears the risk?
  - In the UK and many other countries, much of the risk falls on the radar operator
  - Causes resistance to a new solution
- Incentive
  - Often minimal benefit for radar operator
- Resources
  - Rare to have wind farm mitigation personnel at an airport
  - Issue often falls to people with little time

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Obstacles for New Mitigation

- Regulation
  - The approval process for a new technology is not straightforward
  - Unknown time and cost constraints
- Political climate
  - Uncertainty over future of wind farms can deter radar operators from committing to mitigation solutions
- Money
  - New solutions are often cost-prohibitive for small or medium scale developments

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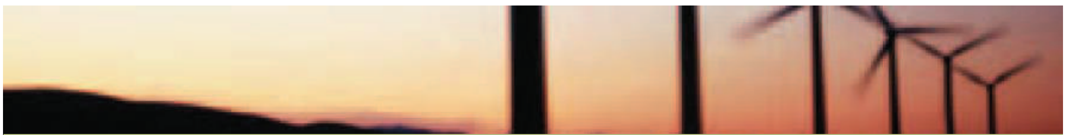

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October 2015

Thank you!

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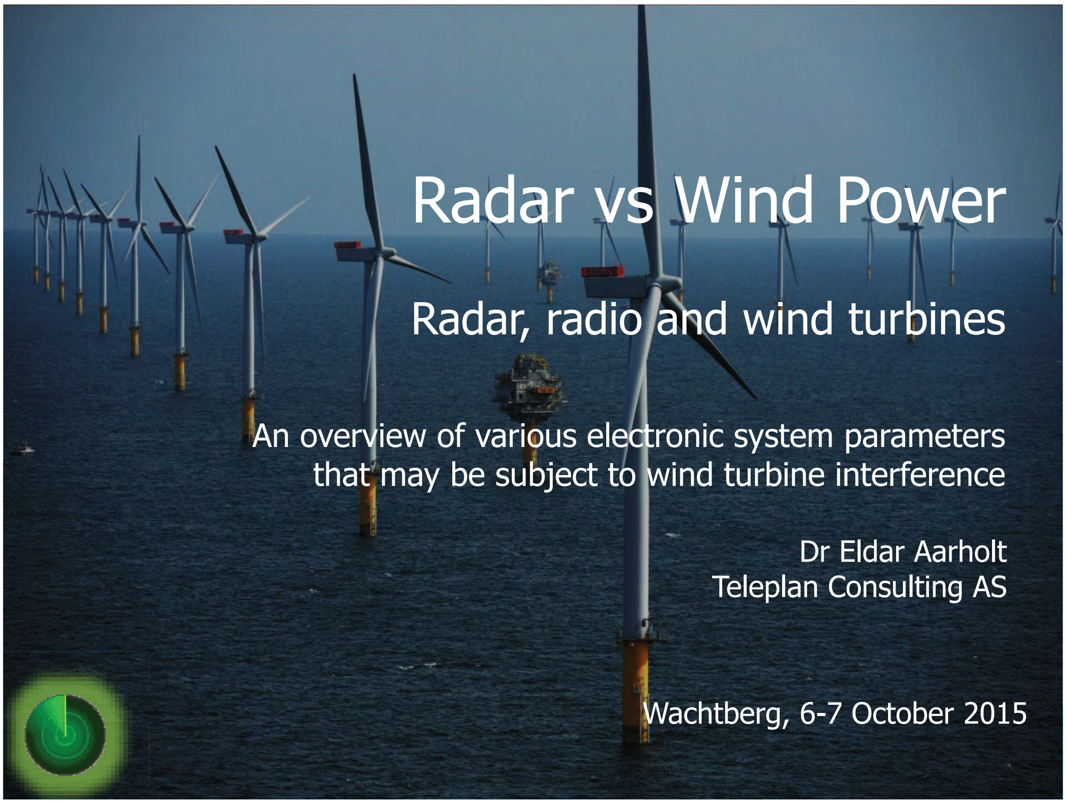
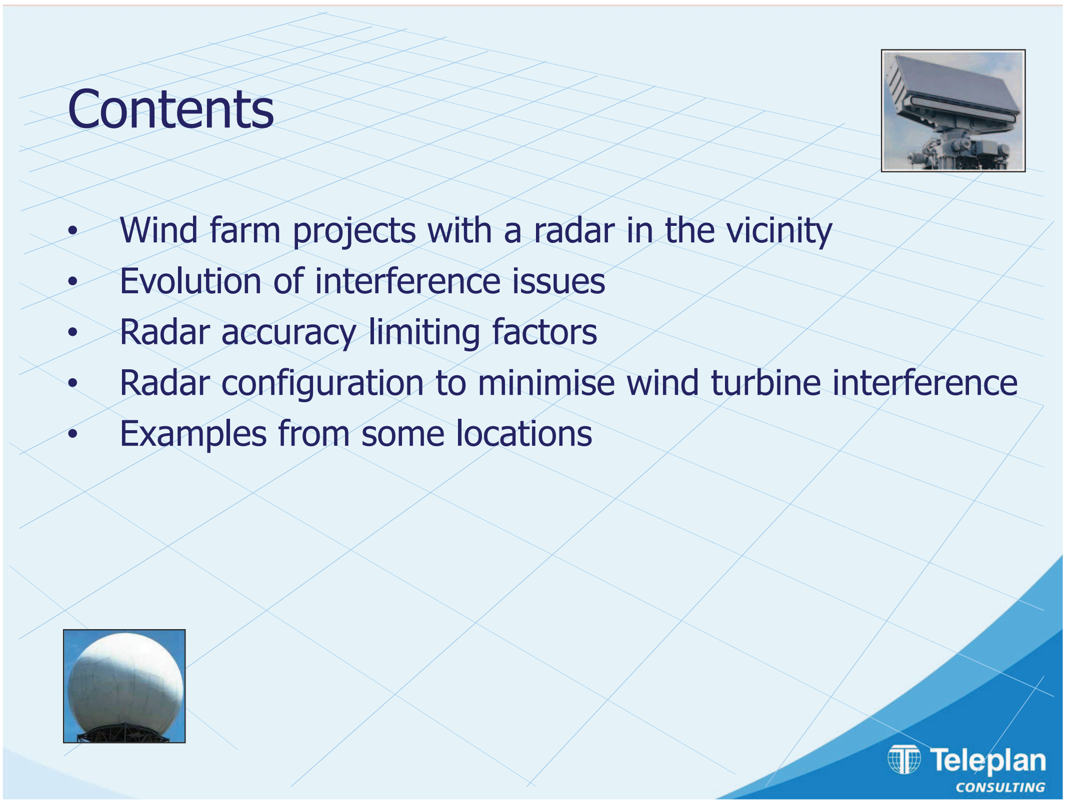

Radar vs Wind Power
Radar, radio and wind turbines
An overview of various electronic system parameters that may be subject to wind turbine interference
Dr Eldar Aarholt
Teleplan Consulting AS
Wachtberg, 6-7 October 2015


Contents
• Wind farm projects with a radar in the vicinity
• Evolution of interference issues
• Radar accuracy limiting factors
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Wind farm projects in Norway with a radar in the vicinity

- From 2004 to 2015, Teleplan has evaluated more than 30 wind farm projects with a radar in the vicinity
- About 50 % were approved, 25 % rejected and the rest undecided or abandoned
- Time from application to decision varied from two to eight years

Approximate locations shown in Google-Earth

Some statistics related to radar and wind farms

- During the period 2005 – 2007, most wind farm license application were rejected in Norway
- During the period 2008 – 20014, most wind farm license applications were approved in Norway

- The reason may be twofold;
  - Wind farm developers have become better in choosing low conflict projects
  - Knowledge of interaction between radar signals and wind turbines have become better understood for all parties

Some established facts

- If a radar is located in line of sight to a wind turbine, the radar will always be affected by the wind turbine
- The radar will receive a reflected signal from the tower, and a weaker reflected signal of varying frequency (Doppler) from the blades
- During radar picture production, signal disturbances can be seen at the geographical location of the wind turbine unless smaller disturbances have been removed by signal processing
- It is very difficult to remove signals from the wind turbine without removing the detection of other object in the same position as the wind turbine
- Usually, the radar cannot detect other objects at the same location as the wind turbine
- Unless sensor owner accepts some negative effects from the wind turbine, they can never be located in the vicinity of a radar

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Issues in 2003 and 2015

Effect	2003	2015
Blocking	Wind turbines stop and block the radar beam	...to a very small extent; 10 % blocking corresponds to only 0.46 dB reduced power
Shadowing	Wind turbines create radar shadow	...to a very small extent; a weak radar shadow a few hundred metres directly behind the tower
Signal strength	Reflections from wind turbines can destroy the radar receiver	...is so weak that it could not possibly destroy the radar
Clutter	Wind turbines contribute to noise in the radar picture and makes the radar useless	...at the location of the wind turbine and a few hundred metres in front and behind the tower
Doppler signal	Wind turbines introduce false targets	...at the location of the wind turbine and a few hundred metres in front and behind the tower
Reflections via wind turbine	Multipath propagation contributes to real target position error	...is a rarely detected phenomena where the reflection usually is weaker than the noise floor
Exclusion zone	Restriction closer than 10 km, alternatively no restrictions	...depends on the location

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Signal blocking

- Signal blocking from a wind turbine is a function of its physical size and the radar main beam area at a given distance
- Signal attenuation as a function of blocking percentage:

$$\Delta P = 10 \cdot \log\left(\frac{100\% - B\%}{100\%}\right)$$

- where ΔP equals reduced power and B is blocking percentage
  - 25 % blocking corresponds to 1.25 dB reduced power
  - 10 % blocking corresponds to 0.46 dB reduced power

- Such low values are almost impossible to measure outside a microwave laboratory
- International documentation does not consider blocking to any extent, because the level of signal blocking from a wind turbine can be easily calculated

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Shadowing

- During the years 2007-2009, several experiments were conducted to measure the radar shadow behind a wind turbine
- It is measured to be up to 2 dB a couple of hundred metres behind the tower in a width comparable to the tower diameter
- Shadowing is hardly measurable for longer distances
- Shadowing is not an electromagnetic issue, but an effect introduced by the radar hardware and/or software
- Shadowing behind wind turbines will not have any significant impact on the ability of the radar to detect targets*

* Norwegian Defence Research Establishment, report 2007

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Clutter

- Clutter can result in increased number of unwanted reflections from a wind farm, both from the motionless towers as well as from the rotating turbine blades contributing to a significant Doppler frequency spectrum
- This may result in lower sensitivity to detect objects located near or above the wind farm and especially at low antenna elevation angles
- Conventional 2D radars are more susceptible to this type of disturbance as compared to 3D radars that can direct the antenna in different elevations, thereby avoiding to look directly at the wind farm

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Reflected signal strength

The reflected power P_{ref} from a wind turbine in the radar receiver can be calculated using the radar equation:

$$P_{ref} = \frac{\sigma \cdot F^2 \cdot G_t \cdot P_t \cdot G_r \cdot \lambda^2}{(4 \cdot \pi)^3 \cdot D^4} \text{ W}$$

- where σ is the monostatic radar cross section (m^2), F is the terrain loss factor between radar and wind turbine, G_t is the transmitter antenna gain, P_t is the transmitter power (W), G_r is the receiver antenna gain, λ is the radar wavelength (m) and D is the distance between radar and wind turbine (m)
- Typical values are: σ = 100 m^2, F=1, G_t = G_r = 45 dB = 31623, P_t = 250 000 W, λ = 0.0536 m, D = 2500 m, π = 3.1416

- Reflected power at the radar receiver equals 0.000926 W (-0.34 dBm), a signal strength that cannot damage the radar receiver
- To damage the radar receiver, the signal strength required is about +53 dBm (200 000 times stronger)
- The corresponding required RCS is about 20 million m^2

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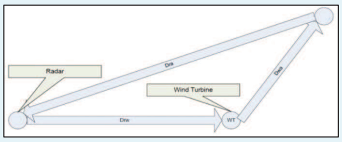
Multipath signal strength



The reflected multipath power P_{ref} from a wind turbine in the radar receiver can be calculated using the following equation:

$$P_{ref} = \frac{\sigma_{a2}.\sigma_{w1}.F_{rw}.F_{wa}.F_{ar}.G_t.P_t.G_{rs}.\lambda^2}{(4.\pi.)^4.D_{rw}{}^2.D_{wa}{}^2.D_{ra}{}^2} \text{ W}$$

- where σ_{a2} is the object radar cross section (1 m^2), σ_{w1} is the radar cross section of the part of the wind turbine seen by the radar (100 m^2), $F_{rw}=F_{wa}=F_{ar}=1$ are terrain loss, G_t is transmitter antenna gain (45 dB), P_t is transmitter power (250 kW), G_{rs} is receiver antenna gain (45 dB), λ is the radar wavelength (0.0536 m), D_{rw} is distance from radar to wind turbine (2500 m), D_{wa} is distance from wind turbine to the object (1000 m), and D_{ra} is distance from the object to the radar (3500 m)
- Typical weather radar noise floor is -108 dBm with a side lobe attenuation of -28 dB

- Using relevant values for a typical wind turbine at a distance of 2500 m from a weather radar, the received signal strength becomes -130 dBm.
- The objects radar cross section can be increased 22 dB before the signal strength approaches the noise floor
- Hence, multipath reflections from a wind turbine will very seldom affect the radar

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So what is the problem

- Blocking is not an issue
- Shadowing is not an issue
- Clutter may be a 2D radar issue
- Reflected signal strength is not an issue
- Multipath reflections is not an issue
- The way people think is an issue

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Radar configuration to minimise wind turbine interference

- Use short radar pulses (f.ex 0.5 μs pulse width corresponding to 75 m range resolution)
- Use short signal processing range intervals at locations of wind turbines or other unwanted reflections
- Calibrate noise floor for various antenna elevations
- Remove known signal reflections either using range/azimuth gating or in radar software

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Wind turbine positioning to minimise radar interference

- Position the wind turbine out of sight from the radar
- Position the wind turbine low in terrain, preferably so that the wind turbine blade highest point is lower than the radar antenna centre
- Position the wind turbines on a straight line as seen from the radar position
- Cover strong reflectors on the wind turbine construction with microwave absorbers
- Position the wind turbine so that mirror reflections are avoided

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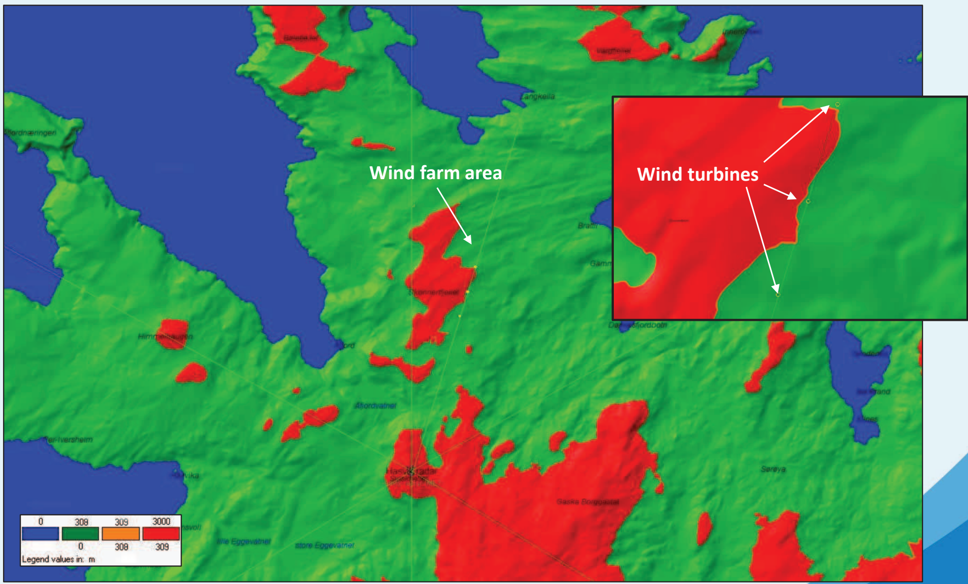
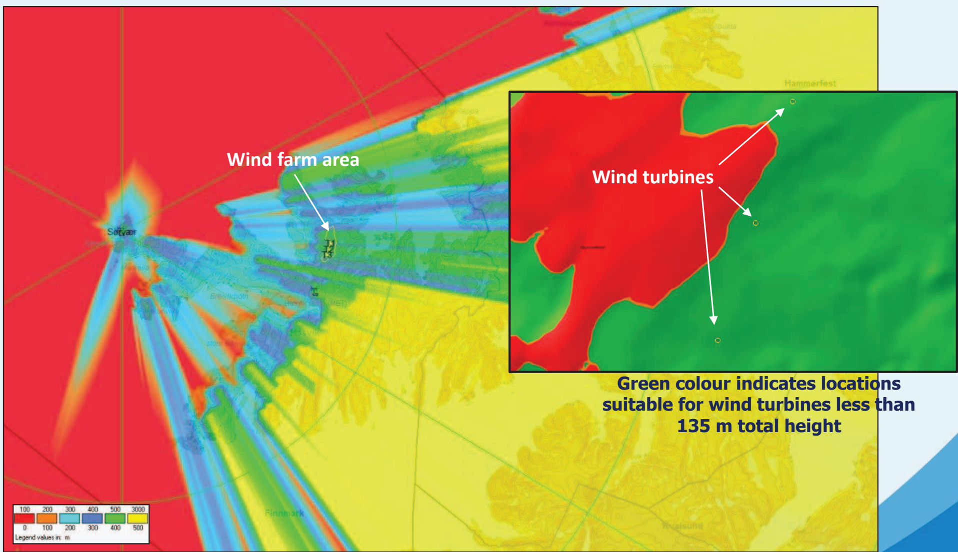
Examples of wind turbine positioning in a straight line within a wind farm area and lower than the radar antenna horizontal plane



Green colour indicates locations suitable for wind turbines less than 135 m total height

Examples of wind turbine positioning within a wind farm area and located lower than radar line of sight



Wind turbine towers are positioned so that turbine blades are lower than the line of sight as seen from the radar due to natural obstacles

Wishes for the next step

- Improve understanding of radar operation and limitations using real-time experiments, in particular radars for meteorological use
- More data from radar interference tests
  - One weather radar site in northern Norway will be used for wind turbine test purposes
  - One military air surveillance radar site in south-western Norway will be used for wind turbine test purposes
  - Deployment of wind turbine radar echo simulator may be an alternative to test radar resilience against wind turbine interference

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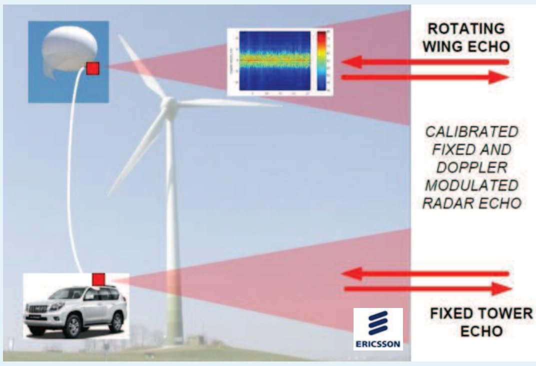
Wind turbine radar echo simulator



System description:
- Precision calibrated high power coherent radar target generator with programmable Doppler signature

Frequency bands:
- 8-12GHz, 1-3GHz

Radar Cross Section (RCS):
- Span: 0.5 – 300.000m²
- Accuracy: 0.1m²
- Fixed RCS /Blade flash mode

Doppler velocity
- Span: 0 – 500 m/s
- Accuracy: 0.02 m/s
- Modulation: Fixed Doppler/ Rotating wing mode

Deploy the echo simulator to mimic the presence of wind turbines

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Conclusion
• Radar vs Wind Power
• Yes please, both...
Thank you

Algorithms

Radar, radio and wind turbines

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01.10.2015

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Typical PSR radar data

Radar parameters PSR*	Values
Typical radar data	ASR-8
Radar frequency (f)	2.7-2.9 GHz
Wavelength (l)	~0.1 m
Peak power dBm = ((10xLog_{10}(Power Watt)) + 30)	1 MW (+90 dBm)
Antenna gain (log / lin) Antenna gain = $\pi^2 * d^2 / l^2 * k_{eff}$ dBi = ((10xLog_{10}(antenna gain))	40 dBi / 10000
Antenna beam width $_{(horizontal)}$ (-3dB)	1.7°
Antenna width (d)	4.5 m
Antenna centre height above ground	~15 m
Instrumented range	111 km (60 NM)
Pulse length	0.5-6.0 ms
Antenna centre (masl)	TBD

* Merill Skolnik, Introduction to Radar Systems, McGraw-Hill, page 204, 1981

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Typical SSR radar data

Radar parameters SSR*	Values
Radar type	Cassidian MSSR 2000i
Radar frequency (f)	TX 1030 MHz / RX 1090 MHz
Wavelength (l)	0.2913 m
Peak power dBm = ((10xLog_{10}(Power Watt)) + 30)	2000 W (+63 dBm)
Antenna manufacturer	Antenna Associates ca 4.2 m (14 ft)
Antenna gain (log / lin)	30 dBi / 1000
Antenna beam width $_{(horizontal)}$ -3dB	5.0°
Antenna centre height above ground	TBD
Instrumented range	278 km (150 NM)

*Eurocontrol Guidelines v1.2, Annex D3, page 61, 09.2014

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Typical radio link parameters

Radio link component	Values
Antenna type	Parabolic
Antenna diameter	2 m
Radio link frequency (f)	4.5 GHz
Wavelength (l)	0.067 m
Typical peak power dBm = ((10xLog_{10}(Power Watt)) + 30)	100 W (+50 dBm)
Antenna gain (log / lin)	37 dBi / 5000
Antenna beam width $_{(horizontal)}$ -3dB	2.4°
Antenna centre height above ground	TBD
Typical link distance	35 km

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Typical radio communication system parameters

Communications components	Values
FM radio frequency (f)	100 MHz
Typical peak power dBm = ((10xLog$_{10}$(Power Watt)) + 30)	10 kW (+70 dBm)
DAB radio frequency (f)	229 MHz
Typical peak power dBm = ((10xLog$_{10}$(Power Watt)) + 30)	2 kW (+63 dBm)
TETRA radio frequency (f)	390 MHz
Typical peak power dBm = ((10xLog$_{10}$(Power Watt)) + 30)	50 W (+47 dBm)
Digital TV frequency (f)	700 MHz
Typical peak power dBm = ((10xLog$_{10}$(Power Watt)) + 30)	50 kW (+77 dBm)
Mobile phone frequency (f)	900/1800 MHz
Typical peak power dBm = ((10xLog$_{10}$(Power Watt)) + 30)	20 W (+43 dBm)

Eurocontrol PSR recommendations

- Eurocontrol recommend an exclusion zone of 500 m from primary radar, and for distances from 500 m to 15 km, a detailed assessment should be performed. For distances more than 15 km and within maximum instrumented range and line of sight, it is considered sufficient with a simple assessment containing the antenna position, frequency band and CFAR algorithm.

Zone	Zone 1	Zone 2	Zone 3	Zone 4
Description	0 - 500 m	500 m - 15 km and in radar line of sight	Further than 15 km but within maximum instrumented range and in radar line of sight	Anywhere within maximum instrumented range but not in radar line of sight or outside the maximum instrumented range.
Assessment Requirements	Safeguarding	Detailed assessment	Simple assessment	No assessment

Eurocontrol Guidelines v1.2, section 4.2.1, page 28, 09.2014

Eurocontrol SSR recommendations

- Eurocontrol recommend an exclusion zone of 500 m from secondary radar, and for distances from 500 m to 16 km within maximum instrumented range and in line of sight, a detailed assessment should be performed. For distances more than 16 km or not in line of sight, no assessment is required.

Zone	Zone 1	Zone 2	Zone 4
Description	0 - 500 m	500 m - 16 km but within maximum instrumented range and in radar line of sight	Further than 16 km or not in radar line of sight
Assessment Requirements	Safeguarding	Detailed assessment	No assessment

Eurocontrol Guidelines v1.2, section 4.2.2, page 31, 09.2014

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The electromagnetics of wind turbines

The following studies illustrate relevant relationships of wind turbine tower radar cross section (RCS), signal shadowing and radar signal blockage

- Qinetiq, Gavin J Poupart, Wind farm impact on radar aviation interests – final report, 2003, page 60, section 7.3.4.2 (radar cross section) and p B-12, section B.5 (shadowing)
- Qinetiq, Martin J Howard, Colin Brown, Results of electromagnetic investigations and assessments of marine radar, communications and positioning systems undertaken at the North Hoyle wind farm by Qinetiq and the Maritime and Coastguard Agency, Qinetiq/03/00297/1.1, MCA MNA 53/10/366, 22. November 2004 (radar cross section, shadowing, communication systems, navigation systems)
- Radar and Wind Farm Solutions, AMS, England, IEA London, 17-18 March 2005
- IEA topical expert meeting on radar, radio and wind turbines, Amsterdam 18-19 November 2009

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Representative measured electromagnetic values for wind turbine considerations

- If the tower side slant angle is 0.8º, the tower RCS becomes about 100 m^2, and it is reduced as a function of increasing slant angle (i.e. 10 m^2 at 2.7º slant angle). This is consistent with typical RCS values for large transport aircraft such as the Boeing 747.
- The turbine blades constitute a much weaker radar signal return than that of the tower (in the order of 30 dB weaker)
- Blockage and shadowing from a wind turbine is very small. The shadow from a wind turbine tower extends only a few hundred meters directly behind the tower with a width comparable to the tower diameter.

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The electromagnetics of wind turbines (1)

Radar detection

- There is no uncertainty about the fact that radars can detect wind turbines

Signal strength

- Strong reflected signals from a wind turbine will mask reflected signals from other targets in close proximity to the tower

Range accuracy

- As a rule of thumb, radar range accuracy is proportional to the inverse of the radar bandwidth, while the antenna beam width regulates the azimuth accuracy.
- A wind farm does not influence the radar range accuracy

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The electromagnetics of wind turbines (2)

Range-Azimuth Gating (RAG)

- Many modern radar systems are equipped with a functionality called "range-azimuth gating"
- The radar will not receive or process signals from certain directions and range intervals

Shadowing

- Radar shadow is measured to be up to 2 dB reduced signal level a few hundred meters behind the wind turbine tower at a width comparable to the tower diameter
- The radar shadowing is hardly measurable for longer distances

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Typical wind turbine data

- A typical wind farm layout may consist of 10 to 50 or more wind turbines located about 300-400 m apart with heights varying from 100 m to 150 m

Component	Turbine type
Tower	Conical tubes made of steel
Nacelle height	100 m
Rotor diameter	100 m
Maximum height about ground	150 m
Tower diameter at ground level	5.0 m
Tower diameter at nacelle	3.5 m
Tower slant angle	0.43°
Rotor revolutions	~6-18 rev/min

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Received reflected power P_{ref} from a wind turbine

$$P_{ref} = \frac{\sigma \cdot F^2 \cdot G_t \cdot P_t \cdot G_r \cdot \lambda^2}{(4 \cdot \pi)^3 \cdot D^4} \text{ W}$$

- where σ is monostatic radar cross section [m^2], F is the terrain loss between radar and wind turbine, G_t is the transmit antenna gain, P_t is the transmitted power [W], G_r is the receiver antenna gain, λ is the radar wavelength [m], and D is the distance between the radar and the wind turbine [m]
- Typical values are: σ = 500 m^2, F=1, G_t = G_r = 40 dB = 10000, P_t = 1 000 000 W, λ = 0.1 m, D = 7100 m, π = 3.1416
- With the above values, the reflected energy (P_{ref}) in the antenna equals -10 dBm, a signal power that is well inside any radar specifications.
- If the transmitted power is different from 1 MW (+90 dBm), or the radar cross section is different from 500 m^2, the received power in the antenna will vary accordingly

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Secondary radar considerations

- An air traffic transponder will answer the secondary surveillance radar signal if the received signal level is stronger than -71 dBm (in the literature, somewhat different reference levels down to -77 dBm are used)
- The reflected signal power from a wind turbine tower is a function of the radar transmitted power, the wind turbine radar cross section, the radar signal angle of incidence and the distance between the radar and the air transponder

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Received reflected power P_{ref} from a wind turbine received by an air transponder

$$P_{ref} = \frac{\sigma \cdot F_{tw} \cdot F_{wr} \cdot G_{tw} \cdot P_t \cdot G_{rw} \cdot \lambda^2}{(4 \cdot \pi)^3 \cdot {D_{tw}}^2 \cdot {D_{wr}}^2} \text{ W}$$

- where s is the wind turbine bistatic radar cross section [100 m^2], F_{tw}=F_{wr}=1 is the terrain loss, G_{tw} is the transmit antenna gain [30 dBi = 1000], P_t is the transmitted power [2000 W], G_{rw} is the receiver antenna gain [0 dB = 1], λ is the radar wavelength [0.291 m], D_{tw} is the distance between the radar and the wind turbine [7100 m], and D_{wr} is the smallest distance from the wind turbine to the transponder [5250 m]
- Using the above values, the reflected power in the air transponder becomes -82.1 dBm, which is weaker than the signal of -77 dBm that would trigger a response from the air transponder
- Distance between a wind turbine and an air transponder shorter than 5250 m in relation to signal reflections is not relevant as documented by Eurocontrol

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Radar cross section

- Radar cross section (RCS) is the measure of a target's ability to reflect radar signals in the direction of the radar receiver, i.e. it is a measure of the ratio of backscatter density in the direction of the radar (from the target) to the power density that is intercepted by the target

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

- Maximum RCS (optical mirror reflection) for a cylindrical wind turbine tower of height 80 m, radius 2 m and radar frequency 3 GHz [λ=0.1 m] equals 804 248 m^2. However, due to the tapering of the tower as well as the non-coherent adding of radio wave reflections from the tower structure, the perceived RCS is usually several orders of magnitude less

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Antenna gain

- The gain of a parabolic antenna (dbi) in a given direction is the amount of energy radiated in that direction compared to the energy an isotropic antenna would radiate in the same direction when driven with the same input power

$$G_{dBi} = 10\ \log_{10}\left(\frac{\eta \cdot 4 \cdot \pi \cdot A}{\lambda^2}\right)$$

- where η is efficiency [55 %], λ is wavelength [0.1 m] at 3 GHz, and A is physical aperture area [radius r = 1 m].
- The isotropic antenna gain equals $10 * \log_{10}(0.55 * 4 * \pi * (\pi r^2) / \lambda^2)$ = 33.4 dBi.

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Near field distance

- For a horn or dish antenna, the near-field distance* can be taken as:

$$D_{nf} = \frac{N_{nf}\eta D_a^2}{\lambda}$$

- where N_{nf} is a constant, typically 1 or 2, setting the degree of conservatism, η the efficiency of the antenna (in the range 0.0 to 1.0), D_a is the diameter of antenna physical aperture, and λ is the wavelength.
- The limit for near field considerations, when N_{nf} equals 2 and η equals 1 at λ = 0.067 m [4.5 GHz] and 2 m diameter antenna, is 120 m.
- Using a 3 m diameter antenna, the near field limit becomes 270 m.
- Hence, a wind turbine will usually be located in the antenna far field.

*D F Bacon, Fixed-link wind turbine exclusion zone method, section 1.3, page 4, 2002

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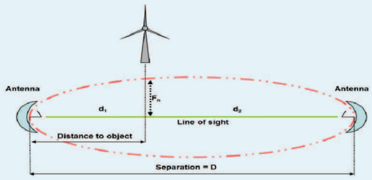
Fresnel zone distance



- Diffraction effects will be insignificant if obstructions are kept outside a volumes of revolution around a radio path know as a Fresnel zone. The extent of the Fresnel zone is calculated using the following equation:

$$F_n = \sqrt{\frac{n\,\lambda\,d_1\,d_2}{d_1 + d_2}}$$

- where F_n is the n^{th} Fresnel zone radius [m], d_1 is the distance from $antenna_1$ to the wind turbine [m], d_2 is the distance from the wind turbine to $antenna_2$ [m], and l is the wave length of the radio signal [m].
- As can be seen from the equation, the extent of the Fresnel zone is a function of wavelength and distances.
- A distance of more than one Fresnel zone is considered safe distance. Often 1.5 or 2 Fresnel zones are used to allow for some margin in calculations.

*D F Bacon, Fixed-link wind turbine exclusion zone method, section 1.3, page 4, 2002

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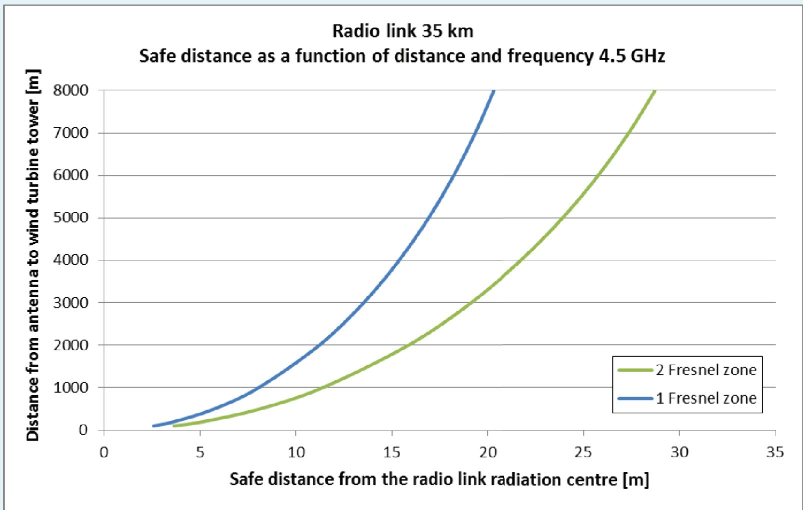
Safe distance from a typical 4.5 GHz radio link



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Broadcast path loss

- In telecommunication, free-space path loss (FSPL) is the loss in signal strength of an electromagnetic wave that would result from a line-of-sight path through free space (usually air), with no obstacles nearby to cause reflection or diffraction.

$$FSPL = \left(\frac{4\pi \cdot d}{\lambda}\right)^2 = \left(\frac{4\pi \cdot d \cdot f}{c}\right)^2$$

$$FSPL(dB) = 10 \cdot \log_{10}\left(\left(\frac{4\pi}{c} \cdot d \cdot f\right)^2\right)$$

- where c is speed of light [$3e^8$ m/s], d is distance from the transmitter [f.ex 16 000 m], f is frequency [f.ex $700e^6$ Hz] and λ is the radio frequency wavelength [m].
- The isotropic path loss equals -113.4 dBi using the above values.

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