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Final Year Project Report
Specialised Master in Architecture of Electronics and Computing Complex Systems
Assessment Of The Wind Farm Impact On The Radar

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Declaration

I hereby declare that I am the sole author of this report. To the best of my knowledge and belief, this report contains no material previously published or written by any other person, except where due reference is given in the text of the report.

This document has been written during an internship working for Thales Air Systems in collaboration with École Nationale Supérieure des Ingénieurs des Etudes et Techniques d’Armement (ENSIETA).

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Preface

Fortune is arranging matters for us better than we could have shaped our desires ourselves, for look there, friend Sancho Panza, where thirty or more monstrous giants present themselves, all of whom I mean to engage in battle and slay, and with whose spoils we shall begin to make our fortunes; for this is righteous warfare, and it is God’s good service to sweep so evil a breed from off the face of the earth [13].

- Don Quixote about windmills

The made-up history written in 1605 repeats itself nowadays. However, in contrast to delusions of Don Quixote[1], modern wind turbines present the real challenge for the radar industry. In comparison with more than century history of radars, wind turbines have appeared relatively not long ago. In terms of the radar, wind turbines differ from known nature and human made objects. They can be as big as an Airbus A380, the velocity of their blades could be compared with an aircraft speed. It leads to the new problem for the radar detection and tracking. It concerns the majority of radars - civil and military, surface and airborne, 2D and 3D. Wind farms can have hundreds of wind turbines. One wind farm can cover a few square kilometres. Each part, each turbine makes the signal, which interfere with the radar. Although wind farms are, evidently, stationary, they influence the filters, e.g. Kalman filter, and do not let track an airplane. It is not easy to recognise the target even for a human as well. The operator observes the same signals from turbines. In fact, this problem concerns the security and safety. Difficulties for military radars threaten the national security. For example, it is difficult enough to detect the target flying at an extremely low height. The wind farms make this task even more complex. On the other hand the problem of the safety consists in difficulties for the air traffic management. Primary radars cannot recognise the aircraft in the area of wind farm. It means that for some time the operator has not the necessary information. Considering that every second there are thousands of airplanes in the air, one can see the scale of this challenge. At the same time the wind power is considered as a source of renewable energy. Nowadays, countries devote attention to the development of this area. Consequently, one can predict a further spread of wind farms.

Generally, this work shows the means to evaluate the wind farm impact on the radar. It proposes the set of tools, which can be used to realise this objective. The big part of report covers the study of complex pattern propagation factor as the critical issue of the Advanced Propagation Model (APM). Finally, the reader can find here the implementation of this algorithm - the real scenario in Inverness airport (the United Kingdom), where the ATC radar STAR 2000, developed by Thales Air Systems, operates in the presence of several wind farms. Basically, the project is based on terms of the department "Strategy Technology & Innovation", where it has been done.

Also you can find here how the radar industry can act with the problem engendered by wind farms. The current strategies in this area are presented, such as a wind turbine production, improvements of air traffic handling procedures and the collaboration between developers of radars and wind turbines. The possible strategy for Thales as a main pioneer was given as well.

Evgeny D. Norman
Limours
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[1]Painting: Honoré Daumier, Don Quixote, 1868, exhibited in Musée d’Orsay.
Acknowledgements

“We had the best of educations - in fact, we went to school every day.”
“I’ve been to a day-school, too,” said Alice; “you needn’t be so proud as all that.”
“With extras?” asked the Mock Turtle, a little anxiously.
“Yes,” said Alice, “we learned French and music.” [2]

- Alice and the Mock Turtle

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Summary

The accent of this master’s report is made on the solution of wind farm problematic, rather than on the presentation of the work that has been done. However, everywhere the reader can find references to original solutions which are given in DVD. The full articles, brochures and presentations, which have references to bibliography in the text, can be found in DVD.

Following is a brief synopsis of the report:

Chapter 1. This gives an historical and general introduction to the problematic of wind farms within the framework of the radar industry. Initial objectives for the internship are described. The Chapter contains the presentation of Thales Air Systems, its Surface Radar unit and department "Strategy Technology & Innovation" - the initiator of this topic.

Chapter 2. State of the art is given here. A few strategies to mitigate the effect of wind turbines are shown. They have been compared and evaluated. Finally, we have chosen the only strategy, which is be examined in the current report. Basically, this Chapter is based on existed recent publications and presentations in this area.

Chapter 3. In this chapter we show the proposed means as a solution of chosen strategy. This means consists of a few consecutive stages. Each stage is based on the tool. Subsections 3.2.1 - 3.2.4 present these tools. The Section 3.3 shows how to use them. 2D, pseudo 3D and vector PE propagation models are given there as well.

Chapter 4. One of the tools of Chapter 3 - Advanced Propagation Model - was studied in details. The output of APM is the pattern propagation factor. Technically, Chapter is of great value for this master’s report. A new complex pattern propagation factor was defined and an existing one was replaced.

Chapter 5. Here we give an application of the assessment means given in Chapter 3. This is a real scenario with a radar of Thales, wind farm of Vestas and environment in United Kingdom. As an outcome the influence of wind farm was given in terms of RCS of each wind turbine. Recommendations to reduce undesirable action of the wind farm were presented as well.

Chapter 6. This Chapter has recommendations for the further work.

Chapter 7. Here we conclude the result of this project.
Abbreviations

ALBEDO - software that calculates RCS (not an abbreviation)
APM - Advanced Propagation Model
APPF - Amplitude of Pattern Propagation Factor
AREPS - Advanced Refractive Effects Prediction System
ASTRAD - Architecture & Simulation Tool for Radar Analysis & Design
ATC - Air Traffic Control
ATM - Air Traffic Management
AWEA - American Wind Energy Association
BWEA - British Wind Energy Association
CAD - Computer-Aided Design
DTED - Digital Terrain Elevation Data
ENSIETA - École Nationale Supérieure des Ingénieurs des Etudes et Techniques d’Armement
IEEE - Institute of Electrical and Electronics Engineers
FE - Flat Earth
FFT - Fast Fourier Transform
GUI - Graphical User Interface
NURBS - Nonuniform Rational B-Spline
PCT - Patent Cooperation Treaty
PE - Parabolic Equations
PPF - Pattern Propagation Factor
PPPF - Phase of Pattern Propagation Factor
RAM - Radar Absorbing Materials
RCS - Radar Cross Section
RO - Ray Optics
SSR - Secondary Surveillance Radar
ST&I - Strategy Technology & Innovation
TEMPER - Tropospheric Electromagnetic Parabolic Equation Routine
VPE - Vector Parabolic Equation
WT - Wind Turbine
XO - Extended Optics
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Chapter 1

General Introduction

1.1 Wind Farms as a New Challenge for the Radar Industry

Wind farms interfere with radar. This leads to unfortunate results for a few interested parties. The radar industry develops new features for its radars trying to mitigate the wind farm influence. Users of existed radar systems receive undesirable signals. Producers of wind turbines and their customers face with limitations and rejections of construction. The government is at the crossroads and has to look for the compromise between the national security and green energy.

The wind turbine has two major features within the framework of the interference with a radar - its size and revolving blades. Blades when turn reflect electromagnetic waves creating Doppler effect, and the radar considers them for moving objects. The wind turbine never stands alone but operates together with the others in the wind farm. It appears as a cluster of secondary targets on radar screens or swamps the screen with multiple returns. However, this is not the main problem. The main difficult is to detect and follow an aircraft in this area. The blades make a very similar signature as radars do because they have close aerodynamic design. The velocity of the blades is also comparable. For example, we take the offshore wind turbine GE Energy 3.6 MW. To estimate we need certain parameters [15] (Table ??).

| Diameter     | 111 m |
|--------------|-------|
| Area swept   | 9677 m² |
| Revolution speed | 15.3 rpm |
| Operational interval | 8.5-15.3 rpm |
| Number of blades | 3 |
| Hub height   | up to 100 m |

Table 1.1: Technical information on GE Energy 3.6 MW

The general formula of an angular velocity is:

\[ \vec{V} = [\vec{\omega}, \vec{r}] \] (1.1)

The angular velocity of the blade’s tip with respect to the centre is determined by perpendicular component of the velocity vector \( V \):

\[ V = \omega r = 2\pi fr = 2 \cdot \pi \cdot (15.3 \text{ rpm}) \cdot 55.1 \approx 88.3\text{m/s} = 317.8\text{km/h} \]

Now we can compare this value with the velocity of the aircraft. For example, the cruising speed of Airbus A330 is 871 km/h. This is a radial speed. When A330 has a tangential component, the radial speed could be close to velocity of the blade. Moreover, each radial point of the blade has its own velocity. It means that the radar receives the frequency range.

Another “source” of velocity is the velocity between the blade and hub. When the blade passes the lower position and is parallel to the hub, due to the airflow it deviates for a short period but this is visible for the radar.

Dimensions of the wind turbine are also comparable with aircraft’s ones. For instance, one of the biggest airplanes - Airbus A380 - has the length 73 m, span 79.8 m, while the length of the normal turbine is 100 m, the diameter is 111 m (Table ??). Actually, a turbine is bigger than a plane, and vertically it is a few times bigger than A380 in front. This leads to the relatively big RCS.

Wind farms will always make undesirable signatures on the radar display. But one can significantly mitigate their influence and this problem will become not very burning issue. It being known that some
Mitigation measures may include modifications to wind farms (such as methods to reduce a radar cross section; and telemetry from wind farms to radar), as well as modifications to radar (such as improvements in processing, radar design modifications, radar replacement, and the use of gap fillers in radar coverage). There is great potential for the mitigation procedures. In general, the government and industry should cooperate to find methods for funding studies of technical mitigations.

Once the potential for different mitigations is understood, there are no scientific hurdles for constructing regulations that are technically based and simple to understand and implement, with a single government entity taking responsibility for overseeing the process. In individual cases, the best solution might be to replace the aging radar station with modern and flexible equipment that is more able to separate wind farm clutter from aircraft. This is a win-win situation for national security, both improving the radar infrastructure and promoting the growth of sustainable energy [11].

Ideas presented in this report correspond to latest directions in a radar development. Solutions need more performance and flexibility from the radar. Digital technologies open new functional capabilities. Among different advantages of digital radar [5] the increased performance, throughput and multi-functionality let implement real time estimation of the wind farm influence.

The problem concerns the regulations of air traffic as well.

Current circumstances provide an interesting opportunity for improving the aging radar infrastructure.

1.2 Thales

1.2.1 History

In 1968, la Compagnie générale de la télégraphie Sans Fil (CSF) and the department of professional electronics of Thomson-Brandt merge and create Thomson-CSF [27]. Between 1970 and 1980, the group signs the first big export contract with Middle Eastern countries and diversifies its activities towards telephonic communications, semiconductor silicon and medical imagery.

In 1982, Thomson SA is nationalized and the group goes in the public sector. Then it meets financial difficulties and debts, which do not cease to grow. This situation takes a turn for the better between 1983 and 1987 thanks to new strategies in professional electronics and defence. The civil telecommunications are closed down and medical sector is sold to General Electric.

In 1987, the fusion of semiconductor sector with Italian IRI-Finmeccanica leads to SGS-Thomson. Between 1987 and 1996, Thomson-CSF, expecting the recession of the defence budget, begins the reorganization of its activities and active politics to external growth of defence sector, generally in Europe, with acquisition of electronic defence activity of Philips in 1989. At the same time the group takes the control over Sextant Avionique. Numerous acquisitions, more modest, extend the industrial presence of the group beyond the national borders, basically in Europe. The contribution of overseas subsidiaries is 5 - 25% of revenue.

In 1998, Aérospatiale, Alcatel and Dassault Industries merge with Thomson-CSF and Thomson SA. This creates on the one hand renewed Thomson-CSF and Alcatel Space on the other hand. Alcatel Space includes the space activities of Alcatel, Aérospatiale and Thomson-CSF. This step lets Thomson-CSF consolidate its main activity, its competitive positions in defence and industrial electronics as well as its implantation in certain European countries (German, Italy, Norway, etc.) As a result of these operations, in 1998, the majority of capital is transformed in the private sector. The part of French state decreases from 58% to 40%, in that way Alcatel and Dassault Industries become a shareholder.

After privatization, the dynamic of “multi-domestic” consolidation of defence activities that was in Europe in 90s goes out from European continent: South Africa, Australia, Korea, Singapore, etc.

The group, thanks to internal growth and acquisitions, deeply modifies its activities. The main direction is aimed to the civil market - information technologies and the most dynamic sector mobile telecommunications. In July 2000, new organisation, based on the defence, woks in three directions: aeronautics and information technologies and service (IT&S).

In December 2000, Thomson-CSF becomes Thales and announces the creation with U.S. Raytheon the first transatlantic joint venture between the defence industry and the world leader of the air defence.

1.2.2 Thales Today

Since 2000, Thales followed the multi-domestic development, by taking the control of some joint ventures in defence and in aeronautics and Alcatel Space. Thales is a defence contractor and a major player in civil and commercial markets around the world. Its businesses are organised by market segment – Aerospace & Space, Defence and Security – and operate as a single organisation, sharing advanced technologies and
CHAPTER 1. GENERAL INTRODUCTION

drawing on complementary capabilities to meet the specific requirements of each customer. Mr Denis Ranque had run the group since 1998 until 2009. Today the Chairman and Chief Executive Officer is Luc Vigneron. Thales is presented in 50 countries. The main countries are pointed out Figure 1.1, it represents about 68000 employees in the world. About 50 % of employees work out of France. 60 % of them are engineers.

Figure 1.1: Global presence

Thales achieved revenue growth of 8% in 2008, sustaining organic growth despite the impact of unfavourable exchange rates, due to the fall in the pound sterling and the dollar against the euro. The annual revenue is 12.7 billion euros. Order intake reached a high level in 2008, growing 14% on a like-for-like basis, with new orders worth 2.7 billion euros for France and 2.8 billion euros for the United Kingdom. At 31 December 2008, the consolidated order book stood at almost 23 billion euros, equivalent to nearly two years of revenues.

Thales operates in three main markets: Defence, Aerospace & Space and Security that represented in Figure 1.2 [21].

Figure 1.2: Activities of Thales

Thales is committed to continuous improvement in the quality of its systems, products and services throughout the life cycle. Underpinning this commitment there are three basic principles:

- Anticipating and answering customer requirements: Thales has a network of commercial experts, key account managers and company-wide platforms all over of the world.
- Supporting customers: Thales guarantees the operational availability and reliability of its products, equipment and systems, throughout their life cycle. Thanks to its international footprint, the company has the capability to provide customers with timely, tailored through-life support and innovative services. A dedicated Internet portal, Customer Online, is also available for customers.
- Measuring the quality of all programme deliverables: Thales conducts regular customer satisfaction surveys and carefully monitors each customer’s supplier ratings.

The group is based on three strategical pillars: its presence in all chains, from equipment and systems to the integration of systems; from technologies to dual applications, with balanced activities between civil
and military areas; and, finally, an international presence, keeping up long-term partnerships with the clients.

Thales has a strong base in Europe with 55,000 employees in 11 countries. In France, the company employs 34,000 people. Thales has an involvement in all the country’s major programmes for air, land, naval, and joint forces (Rafale combat aircraft, FREMM multi-mission frigates, Syracuse III telecommunications system, etc.).

1.2.3 Thales Air Systems

Thales Air Systems division (or simply Air Systems or TR6) develops and gives total solutions of air safety, which bring an answer adapted to needs of civil and military users. It is currently run by Richard Deakin and includes 7 sectors (Weapon Systems, Thales Raytheon Systems, Air Traffic Management Systems, Customer Service, Missile Electronics, Navigation And Airport Solutions and Surface Radar). The division has 6,400 employees and an industrial presence in 14 countries supplemented by an international commercial network.

In civil aviation, the division develops air traffic management systems as solutions for the security of airport zones, helping to land and to navigate aircrafts.

Within the framework of activities of air defence, this division offers a complete range of surface radars, control systems of air operations, solutions of protection of the battlefield and the sensitive sites as well as anti-aircraft defence with both earth and naval weapon system.

The division offers a complete service range of service, of renovation and extension of life as well as services of logistical engineering, etc.

Aerospace markets offer a vivid illustration of the benefits of dual civil/military technologies. Thales is the company with leadership positions in both onboard equipment and ground-based navigational aids and control systems. The company equips all types of aircraft – commercial airliners, military aircraft and helicopters – and is a first-tier partner of the world’s leading manufacturers, including Airbus, Dassault Aviation, Boeing, Sukhoi and ATR, on all of their major programmes. In air traffic management, Thales’ capabilities span the entire flight plan surveillance and security chain, from departure gate through en-route control to arrival gate, in complex and saturated air transport environments. The Air Systems invested a noticeable part in Research and Development.

1.2.4 Limours - Surface Radar

Business Line Surface Radar is run by Jean-Loïc Galle and represents 1,550 employees in France and in Netherlands. The main target is to develop detection systems and service:

- Civil and military radars
- Surveillance radars
- Short and long range radars
- Low frequencies (HF, UHF, etc.) and high bands (L, S, C, X, etc.)
- Passive and active radars

This report was written at Thales Group, Surface Radar unit (SR), department Strategy Technology & Innovation (Figure 1.3), headed by Jean-Philippe Hardange. I worked in collaboration with Gilles Beauquet, Michel Moruzzis and Frédéric Campoy. The responsible for my internship is Frédéric Campoy. He briefed me on the subject and helped with technical issues. Gilles Beauquet provided a number of calculations shown in this work. Also Michel Moruzzis has initiated the topic, guided me and participated in my work. Odile Adrian is in charge of Advanced Developments. She is responsible for my educational programme Thales Academia as well. Mme Adrian proposed this internship according to my preferences and kept motivating me during the work on this report.
In October 2006 Thales Air Systems in Limours has merged with the site in Bagneux. Today there are about 640 employees. Thales Limours combines production activities of Air System and its R&D. Another site of Air Systems is situated in Rungis (head office and R&D).

My office is situated in the building Maxwell (Figure 1.4).

1.3 Objectives of Work

Initially, according to the internship proposition there were three main objectives:

1. Drawing up a state of the art on the 2D and 3D pattern propagation factors (PPF).
2. Defining a complex PPF function replacing an existing one.
3. Analysing the impact on a radar signal using an existing simulation of Air Traffic Management radar and different wind farms scenarios.

List of these objectives has been expanded in order to conduct the complete research that can be used as a complex solution of the problematic regarding wind farms. Therefore, I raised additional goals.

Firstly, it is necessary to make a state-of-the-art that shows the reasons why the wind power industry causes problems for radars. Also in this part we need to show present solutions that allow mitigation of the wind turbine impact on the radar. One of the solutions concerns the initial objectives stated above. So we need to understand when and how this solution can be used, its advantages and disadvantages.

As an example, someone wants to construct the wind farm near the radar. Each turbine interferes with this radar. However, before the construction one can choose the place where the wind farm impact...
will be minimal. The proposed solution must show the right place and give quantitative and qualitative substantiation.

When we know the problematic in general, one must develop the chosen solution. In order to realise that we need to use different software, source code and develop our own one if needed. There is an important element of our solution – a program that propagates an electromagnetic field in atmosphere. It is called Advanced Propagation Model (APM). Complex pattern propagation factor (PPF) function concerns exactly this program. Other elements of our solution are a 3D CAD model of the wind turbine and a software that computes RCS. These different programs can be combined into one solution by connecting elements written, for instance, in Matlab because we need an output data visualisation.

The proposed solution should be tested using the real data of the radar, wind farm and environment. The solution must give the practical result as a recommendation of the best disposition of the wind farm.

Table 1.2 presents the schedule of this project.

| Main objectives                                    | Sub-objectives                                                                 | Week  |
|----------------------------------------------------|-------------------------------------------------------------------------------|-------|
| State-of-the-art                                    | Make internal (Thales Air Systems) state-of-the-art                          | 15-16 |
|                                                    | Make external state-of-the-art                                               | 16-18 |
|                                                    | Present the result                                                           | 18    |
| Receive the complex PPF                            | Develop Matlab script to run APM                                             | 18    |
|                                                    | Analyse APM code                                                             | 19-21 |
|                                                    | Retrieve the phase from FE model of APM                                       | 22    |
|                                                    | Retrieve the phase from FE model of APM                                       | 23    |
|                                                    | Retrieve the phase from FE and XO model of APM                               | 24    |
| Test the solution on the real scenario (simulation) | Collect the necessary data about the radar, wind farm and environment        | 25    |
|                                                    | Prepare different wind farms scenarios                                       | 26    |
|                                                    | Develop Matlab script to run APM for the wind farm                          | 26    |
|                                                    | Develop Matlab script to convert APM output for ALBEDO input                 | 27    |
|                                                    | Receive RCS of wind turbines by ALBEDO                                       | 28-29 |
|                                                    | Analyse the result and corrections                                           | 29    |
| Make a final report                                 | Plan the report                                                              | 30    |
|                                                    | Write all the chapters                                                       | 31-33 |
|                                                    | Correct the text                                                             | 33    |
|                                                    | Make the presentation and DVD                                                | 34    |

Table 1.2: Schedule of the project

Although I have been working according to the schedule that I drew up in 18th week at first I corrected my plan a few times during the work. One can declare that I have done all that I planned excepting the simulation of my project in ASTRAD. I suppose, this is an independent project that can be done by a student, for example. However, all the initial objectives given by Thales Air Systems has been completed.
Chapter 2

Overview of the Subject Matter

2.1 Introduction

After the explication and comprehension of the problem we now show the possible solutions to mitigate the wind turbine influence. There are three main directions to do that. We begin with solution that concerns only the radar (Section 2.2.1). That does not need any relations with third party; it means that the problem can be solved by us as a radar developer. The next solution is connected with producers of wind turbines. The Section 2.2.2 deals with materials and construction of the turbine; how to develop the wind turbine with the goal that it will be less visible for a radar. Other solutions concern administrative aspects: air traffic management and relations with third party (government, wind energy associations, customers, etc.) As a result we show the analysis and comparison of these solutions (Section 2.3). There, we specify one solution that will be considered in next Chapters as a main part of the project.

Also we give different models, which simulate the propagation of electromagnetic field in the space. This section is needed to understand the study given in Chapter 4.

2.2 Strategies to Mitigate the Effect of Wind Turbines

2.2.1 Prediction of the Influence and Signal Processing

It may be possible to use sophisticated radar signal and data processing to overshadow turbine radar returns while preserving returns from objects of interest, such as aircraft. It would seem much easier to do so if the actual configuration of the turbines were known at every instant. The data about the instantaneous state of every turbine (angular velocity, phase, azimuthal orientation of the turbine axis, and pitch angle) could be telemetered to the radar processors and electronics. The turbine-mounted sensors needed for the four quantities listed above are straightforward and not expensive (although not necessarily available without retrofits). Armed with this information, the processor, with the aid of a relatively simple model of the turbine radar cross section, could make a near real time calculation of the time-varying amplitude expected from each turbine in the farm and subtract it coherently from the radar input signal. Significant networking, data processing, and implementation challenges might exist, to be investigated in a research project. We can predict not only the state of wind turbines but also the state of environment using the real time data about wind, temperature, refractivity, reflectivity, terrain, humidity, etc. This will let us predict the influence of the atmosphere and surface on the propagation of electromagnetic waves in order to know the propagation loss in the area of each wind turbine. In that way knowing the electromagnetic field and the state of the wind turbine, we are able to compute RCS and evaluate the influence of entire wind farm. Thus, when the radar receives the signal from a wind farm area, it may estimate a possible presence of the aircraft. Of course it is necessary to provide the “training” of the radar using the measured and computed data, design classifiers and even artificial neural networks. This is the application for the radar signal processing. However, there is the second application of this method. If we want to maintain the radar, with this tool we can take into account the influence of existed wind farms and, finally, choose the balanced place, where the performance of our radar will be higher. On the other side, if the wind farm is maintained, one can come to agreement with neighbour radar operators about the placement of the farm [11].

Exactly this means is examined in details in current report. Further chapters cover the tools needed to realise that, the algorithm of their application and an example.

Also it is possible to deal with the gap fillers. When a wind farm has caused an unacceptable loss of coverage, supplementary gap filler radar could be installed, with appropriate data fusion. The gap filler,
CHAPTER 2. OVERVIEW OF THE SUBJECT MATTER

by allowing a second view of the wind farm radar interference, makes it considerably easier to process this interference out through data fusion.

The radar could be modified to have shorter pulses, a higher pulse repetition frequency (PRF), and local oscillators coherent over a turbine blade period, or multiple elevation beams to avoid ground scraping. The higher PRF allows for painting a given turbine blade with more pulses before the blade rotates significantly. The design of the entire radar signature (including side lobes) needs to take into account the presence of wind farms. Nevertheless, these modifications must not worsen the primary function of a radar - to detect airplanes.

An interesting study has been done by QinetiQ for Swaffham wind farm near the Prestwick Airport.

2.2.2 Wind Turbine Development

Evidently, the wind turbine developers, manufacturers and customers do not care about the effect of wind turbines on the radar. At least they did from recently. The customer makes high demands of the product such as efficiency, performance, reliability, after-sales service, some times low noise pollution, etc. He is far from believing that wind farm can interfere with the radar. From the other hand, to satisfy the client, the developer is looking for competitive solutions working on light and durable materials, strong design, improvements of the aerodynamic model.

Here we examine features of the wind turbine development, which directly affects the radar.

The radar emits electromagnetic beams and receives reflected waves. The reflectivity depends mainly on the material. There is the study about materials used in wind turbines.

Most rotor blades in use today are built from glass fibre reinforced plastic. As the rotor size increases on larger machines, the trend will be toward high strength, fatigue resistant materials. As the turbine designs continually evolve, composites involving steel, glass fibre reinforced plastic, carbon filament reinforced plastic and possibly other materials will likely come into use.

The nacelle contains an array of complex machinery including yaw drives, blade pitch change mechanisms, drive brakes, shafts, bearings, oil pumps and coolers, controllers and more. Basically, the nacelle is built from steal.

Low cost materials are especially important in towers, since towers can represent upto 65% of the weight of the turbine. Prestressed concrete is a material that is starting to be used in greater amounts in European turbines, especially in offshore or near-shore applications. Concrete in towers has the potential to lower cost, but may involve nearly as much steel in the reinforcing bars as a conventional steel tower.

The following observations are based on the results of the material usage analysis. Turbine material usage is and will continue to be dominated by steel, but opportunities exist for introducing aluminium or other light weight composites, provided strength and fatigue requirements can be met. Blades are primarily made of glass fibre reinforced plastic, which is expected to continue. While use of carbon filament reinforced plastic may help to reduce weight and cost some, low cost and reliability are the primary drivers. Increasing the use of offshore applications may partially offset this trend in favour of the use of composites. Prestressed concrete towers are likely to be used more, but will need a substantial amount of steel for reinforcement.

As we can see, basically, wind turbines are built from conductive materials. Its surface reflects electromagnetic waves well enough to be visible for the radar. The visibility of a tower is not critical, since the radar signal processing can separate stationary objects. The main problem, as we have discussed above in Section 1.1 is movable blades. The first idea is to use materials for blades, which will be invisible for the radar. Such a technology is called stealth. Generally, it is used in military area. There are recent researches aiming at reducing reduce the reflectivity of rotor blades.

Using the study presented in Subsection 2.2.1, QinetiQ simulated two turbines - with standard blades and with blades covered by radar absorbing materials (RAM). After RCS has been received. The Figure presents the simulation at 90° yaw and 0° pitch, blades are rotating towards and away from radar, leading edge sees directly at radar. According to calculations, RCS peak is reduced from 30dBsm to 15dBsm.
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The result of the simulation, showing the possible difference between standard blade and the blade with RAM, is shown in Figure 2.2. This is an example of the wind farm in Hare Hill site near Prestwick Airport.

The main shortcoming of this direction is that RAM cover only one frequency band (Figure 2.3). For example, it works for ATC radars but for the military application, where other bands are used, does not.

However, one must mention that there are studies to design optimised composite RAM for operation over wide frequency ranges (typically within the range of 1-100 GHz).

Another barrier of adoption of this technology is its cost. QinetiQ, for instance, claims that the cost penalty for such treatment is of the order of 10% of the total blade cost. We can compare this with the radar installation. Radars, which don’t have the capabilities to mitigate wind farm interference, could simply be replaced, in a phased upgrade of the aging radar infrastructure. The new radar would incorporate multidimensional detection, with greatly enhanced processing, with pulse shapes designed to optimally distinguish between the aircraft and wind farms. The cost of a single radar installation was said to be in the range of €3-8M, to be compared with the €2-4M cost of a single wind turbine. A wind farm can have hundreds of turbines.

For example, we want to install a wind farm with 25 turbines. The price of each is €3M. Using RAM technology, there will be additional expenses 10% - it means €7.5M (€3M·25-10%). The price of this new material is equal to the installation of one or two radars with modern signal processing.

This strategy to mitigate the effect of wind turbines is relatively new. Presently, in 2009, there is no serial production of RAM for wind farms, and there is still no wind farm with this technology. Only
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R&D has been done. Another proposal is to put an active layer on the outside of the turbine blades to modulate dynamically the blade Doppler signature. These modulations, it is claimed, could shift the Doppler frequency spectrum from the blades to lie outside the range of frequencies processed by the radar. It is not known, to us at least, whether such modifications to the outside of the blades would produce unacceptable changes to their aerodynamic properties or whether they would last the lifetime of the blades.

Besides these solutions, there are a few recommendations based on study [29] regarding the design of certain turbine’s parts. The following points summarise some of the results:

- The design of the tower and nacelle should have the smallest RCS signature possible. The RCS of the tower and nacelle can be effectively reduced though careful shaping.
- Large turbines do not necessarily lead to large RCS (i.e. tower height does not greatly affect RCS).
- For a low probability of detection, but a large clutter return, set wind turbines such that they are mainly yawed close to ±90° from the radar direction.
- For a high probability of detection, but a smaller area of clutter, set wind turbines such that they are mainly yawed close to 0° and 180° from radar direction.

2.2.3 Air Traffic Handling Procedure

Regulatory changes for air traffic could make considerable impact on the problem. For example, the government could consider mandating that the air space up to some reasonable altitude above an air-security radar with potential turbine interference be a controlled space, with transponders required for all aircraft flying in that space. This would both solve the problem of radar interference over critical wind farms and would provide a direct way to identify bad actors, flying without transponders [11].

2.2.4 Others

It is evident that the problem involves different actors: radar and wind turbine developers, government and clients both of radars and turbines. The only way to find the solution is to speak and collaborate with each other. In that way they could understand their opportunities and limitations, find the compromise, put forward their arguments. It is necessity at least to outline the possible solution. In order to provide the dialogue one must organise the common symposiums, conferences and meetings. As a result we could receive the standards for the turbine’s construction, methods to estimate the influence of wind farms, start to conduct common research. The actors have to find the balance between the safety of air traffic, national security and the green energy that are one of the national priorities as well. There are many wind energy associations, which are quite influential and usually presents producers, government and clients partially. The radar industry can work through them. Moreover, the wind energy is successfully developing, and associations sponsor many projects every year. There is a demonstrative example in the United Kingdom. The sponsorship has existed there since the beginning of the XXI century. A lot of money has been invested [10] to the development of appropriate solutions for the mitigation of radar interference from wind turbines. Among the grantees one can hear famous names QinetiQ, Vestas Blades Ltd., BAE Systems and many others. Generally, it is the government that makes grants.

It is necessary to create the complete database about every wind farm. These bases could contain coordinates of turbines, their model, characteristics, the information about environment where turbines operate, and so on. The access should be given to producers of radars. For instance, in the United Kingdom there is existed database with the information about all wind farms there. This project has been done by the British Wind Energy Association (BWEA) and is available through www.bwea.com. The access to detailed wind farm information is given only for members.

There is an influential national society in the US - American Wind Energy Association (AWEA) as well. AWEA conglomerates all activities of wind power industry in US. In comparison with the UK market, an american one is bigger and presents more opportunities for cooperation with the radar industry in this field. Interfaces of both BWEA and AWEA are shown in Figure 2.4.
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BWEA has a list of wind farms under construction, operational, consented and submitted. In Chapter 5 we will examine one example of the wind farm in the UK. The information about this farm can be found in BWEA database as well (Table 2.1).

| Online       | September 2006 | Capacity, MW | 30 |
|--------------|----------------|--------------|----|
| Wind farm    | Beinn Tharsuinn | Homes equiv. | 16774 |
| Location     | Highland       | Developer    | Scottish Power |
| Turbine model| Vestas         | Owner        | Scottish Power |
| Power, MW    | 1.65           | Latitude     | 57 48 06 N |
| Turbines     | 17             | Longitude    | 04 19 56 W |

Table 2.1: Operational wind farm in the UK, the data from BWEA

One can see that besides existed turbines there are two turbines under construction in the area of our wind farm constructed by new developer (Table 2.2).

| Date         | February 2009  | Capacity, MW | 4.6 |
|--------------|----------------|--------------|-----|
| Wind farm    | Beinn Tharsuinn extension | Homes equiv. | 2572 |
| Location     | Highland       | Developer    | RockBySea & Midfern Renewbles |
| Power, MW    | 2.3            | Latitude     | 57 48 06 N |
| Turbines     | 2              | Longitude    | 04 19 56 W |

Table 2.2: The UK wind farm under construction, the data from BWEA

This project of BWEA lets us suppose with good reason that the unified complex European database with all wind farms could exist and be needed.

2.3 Comparison and Choice of the Strategy

Finally, we can conclude about directions of solutions of the wind farm problematic. Let us take a look at the all strategies briefly:

- The method of evaluation of the wind farm influence on the radar.
- The improvement of the radar signal processing.
- The wind turbine development using radar friendly solutions (basically materials and design).
- The Air Traffic Handling Procedure.

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1 www.bwea.com/ukwed/operational.asp
2 www.bwea.com/ukwed/construction.asp
• Other collaboration with wind energy industry and implementation of common projects.

It is wrong to suppose that wind power industry is the negative factor for the radar producer. Quite the contrary, it opens the new market and opportunities. Taking into account the activities of Thales, one can declare that Thales Group has already had all the necessary means to make a complex solution. Thus, there is Surface Radar (SR) unit to develop the modern signal processing with updated filters and thresholds. This is a stimulus to replace the ageing radar station with modern and flexible equipment of Thales that can separate the wind farm clutter from the aircraft. Additionally, in particular, ST&I currently carries out the study of impact evaluation. There is ATM unit to provide solutions in ATC. Thales has more international presence than its competitors in this field. Playing the main role in French defence, Thales has an experience of work with French government. This is the time to start the close collaboration with wind energy industry, state and with customers of wind energy. In other words, today the wind power industry is the new unique sector, where the civil and military interests are crossed. Thales has all opportunities to be the pioneer in new technologies, regulations and solutions. In any case all the steps should be made in cooperation with wind energy associations.

However, now Thales is not a leader in “stealth” materials for wind farms (e.g. QinetiQ succeeded there and patented its solutions). But there are doubts that this technology will be competitive in comparison with others.

Below we summarise different aforementioned methods and compare them in Table 2.3.

| Evaluation of Influence | Simplicity of R&D and its cheapness | Simplicity of application and its cheapness | Diversity of applications | Benefit |
|-------------------------|-----------------------------------|--------------------------------------------|---------------------------|---------|
| Signal Processing       | ★                                 | ★                                          | ★★                       | ★★     |
| Air Traffic Management  | ★★                                | ★                                          | ★★                       | ★★     |
| WT Development          | ★                                 | ★                                          | ★★                       | ★ - ★★★|
| • materials             |                                    |                                            |                          |         |
| • construction          | ★★★                               | ★★                                         | ★★                       | ★      |

Table 2.3: Summary of the methods

At R&D level the evaluation of the wind farm impact needs a consolidation of different areas of studies and corresponding software. Also in order to validate the solution it is necessary to conduct research with a real radar station and wind farms. Therefore, the project needs time and economic resources. Talking about the simplicity of its application, we can declare that every case should be considered separately because every time we deal with a new radar, environment and wind farm. In other words every project is unique. However, regarding the diversity of this solution, the uniqueness of the project is an advantage. We can evaluate the wind farm impact for every radar. But the solution usually brings the benefit for the only radar. So we can hide, for example, the wind farm from one radar but it will be visible for others.

The signal processing is complicated in terms of R&D. It includes the complexity of the first solution and also needs new mathematical models. But once the signal processing is done, its application would not be very sophisticated. This solution works for existed types of wind turbines. That is why its diversity is limited. The evolution of the turbine’s design is advancing. Thus, the new design can need the new signal processing.

Rules for the Air Traffic Management do not seem very complicated. But their application is not easy because it concerns many players: airports, air companies and radar developers. It would be very hard to find the common solution and to implement it. The diversity of applications and the benefit are limited by air traffic control. The solution does not concern military radars, for example, which provide the air security and they do not care about air traffic control.

The R&D of “stealth” materials for wind turbines are quite complicated and its new solutions appreciably raise the turbine’s price. Moreover, these materials usually work for the certain frequency range. That is why the diversity of applications is very limited.

Regarding the objectives of this report, we examine the study about the evaluation of the wind turbine influence. The study is considered as a complete and independent method. At the same time this is the necessary part of the signal processing that is described in Subsection 2.2.1. Also the study contains steps, which could be used in development of wind turbines. Therefore, further chapters contain the relevant information for the problem in general.
2.4 2D and 3D Propagation

2.4.1 2D

Basically, the main 2D propagation model is a parabolic equation. The model is implemented in a few software presented on the market: NEMESIS by QinetiQ, AREPS by SSC San Diego, TERPEM by Signal Science Ltd., and TEMPER by the Johns Hopkins University Applied Physics Laboratory. Actually, AREPS and TERPEM are an advanced GUI of the APM code.

The parabolic equation models propagation of energy predominantly in one direction only. The field values at each step are calculated from the field values at the previous step. This is done subject to a radiation boundary condition at the top of the field plane and a terrain boundary condition at the bottom of this plane. Using this method, the shape and the electrical constants of the terrain can be accurately incorporated into the model. The majority of long-range propagation prediction methods in use are 2D and consider propagation along the great circle path between the transmitter and receiver. In details PE is considered in Subsection 4.3.3.

There is another 2D propagation model - ray optics (RO). The model is based on the propagation of beams. The value of the field in the certain point of space is a superposition of all waves - direct and reflected.

2.4.2 Pseudo 3D

As stated above a 2D model neglects the propagation in a horizontal plane and the ray reflects only in a vertical plane. However, it is possible to run the 2D model along the third axe. In this way we can receive a 3D view. Vertical layers that begin from the same point compose the 3D view with an angular step. Also these layers can be parallel if we examine the place at a long distance where the calculating error is negligible. As a result we have the field in the volume. The shortcomings of a 2D propagation apparently remain. The pseudo 3D model does not need any new physical or mathematical theory. It always uses the principals of a 2D model, which can be based on parabolic equations, ray optics, etc. That is why it is called “pseudo”. In other words the pseudo 3D model consists of layers where the electromagnetic field is computed using the 2D model.

Propagation over 2D terrain can be simulated by running APM over multiple 1D azimuths (Figure 2.5) with the terrain assumed to be 1D along each azimuth. The 2D propagation data from these azimuths are then combined to approximate propagation in a 3D environment. It is evident that this approach does not capture out-of-plane scattering and diffraction effects.

2.4.3 Vector PE

A vector version of the parabolic equation method is required to treat general three-dimensional electromagnetic problems. The vector PE is obtained by coupling component scalar parabolic equations
via suitable boundary conditions on the scatterers [26]. This allows accurate treatment of polarisation effects within the paraxial constraints.

The electric and magnetic fields are defined by \( E = (E_x, E_y, E_z) \) and \( H = (H_x, H_y, H_z) \), respectively [37]. For two-dimensional (2D) problems when the fields are independent of the transverse coordinate \( y \), the simplest option is to take is:

\[
\begin{align*}
\psi &= E_y, \text{ for horizontal polarization} \\
\psi &= H_y, \text{ for vertical polarization}
\end{align*}
\]

(2.1)

The determination of \( \psi \) suffices to solve the whole electromagnetic problem: by using the curl equations, all field components are determined and they automatically satisfy the divergence-free conditions.

The situation is, of course, different in three dimensions. Some additional effort is then required to get a solution satisfying Maxwell’s equations. First, we obtain a scalar wave equation for each electromagnetic field component from the curl equations. Second, these component scalar wave equations are coupled through boundary conditions on the scattering object and through the divergence-free condition in order to obtain a well-determined system. In this work, we only examine the case of perfectly conducting scatterers. Then boundary conditions on the object can be written in terms of the electric field only, so that we have a self-contained system of equations to solve for the electric field. The magnetic field can be obtained through the curl equation if required. For a perfect conductor, the tangential electric field must be zero on the object or, equivalently, the electric field must be parallel to the normal. This gives the following system of equations:

\[
\begin{align*}
n_x E_y(P) - n_y E_z(P) &= 0 \\
n_x E_z(P) - n_z E_x(P) &= 0 \\
n_y E_x(P) - n_x E_y(P) &= 0
\end{align*}
\]

(2.2)

where \( P \) is a point on the surface of the scatterer and \( \mathbf{n} = (n_x, n_y, n_z) \) is the outer normal to the surface at \( P \). In terms of the PE reduced scattered field, these conditions become non-homogeneous. For example the first equation of Eqn. 2.2 is written as

\[
n_x u_x^s(P) - n_y u_z^s(P) = -e^{ikz}(n_x E_y^i(P) - n_y E_z^i(P))
\]

(2.3)

where \( E = (E_x^i, E_y^i, E_z^i) \) is the incident electric field.

The three equations in Eqn. 2.2 are not independent, but form a system of rank 2. Hence, we need another equation to ensure unity of the solution. This is provided by the divergence-free condition of Maxwell’s equations:

\[
\frac{\partial E_x^s}{\partial x} + \frac{\partial E_y^s}{\partial y} + \frac{\partial E_z^s}{\partial z} = 0
\]

(2.4)

where \((E_x^s, E_y^s, E_z^s)\) is the scattered electric field. It should be noted here that in the 2D case the fields are automatically divergence-free since we solve for \( E_y^s \) or \( H_y^s \), which do not depend on \( y \). This is no longer true in the 3D case, where the divergence-free condition must be enforced explicitly. Enforcing the divergence-free condition on the object boundary ensures a well-determined system of equations, and we show in the Appendix that the PE solution is then divergence-free everywhere. The parabolic equation formulation avoids the need for direct estimation of the range derivatives in the divergence-free condition, yielding an expression involving points in the transverse plane only. We can rewrite (2.4) as:

\[
\frac{i}{2k} \left( \frac{\partial^2 u_x^s}{\partial y^2} + \frac{\partial^2 u_x^s}{\partial z^2} \right) + i ku_x^s + \frac{\partial u_y^s}{\partial y} + \frac{\partial u_z^s}{\partial z} = 0
\]

(2.5)

Vector PE is implemented by a few institutions: Johns Hopkins University Applied Physics Laboratory, the U.S., University of Birmingham, the UK, the Radio-communications Agency of the Department of Trade and Industry. However, there is no successful application for the atmospheric propagation like 2D models (APM, TERPEM, TEMPER, NEMESIS). The model was generally driven by Andrew A. Zaporozhets [2] and Mireille F. Levy [26].
Chapter 3

Assessment Means

3.1 Introduction

The assessment means is a set of tools (here Section 3.2) combined together in order to evaluate the wind farm impact. Actually, each tool is an independent program: APM, Rhino NURBS, ALBEDO and ASTRAD. We show how to apply them for our needs in Section 3.3. For this reason we develop additional Matlab scripts so that we can estimate the wind farm impact.

3.2 Proposed Tools

3.2.1 Advanced Propagation Model

Advanced propagation model (APM) calculates different characteristics of electromagnetic propagation. It uses the set of input parameters about the source, environment and terrain. The source code is written in Fortran 90. The big advantage of APM is that we have the source code and can correct it for our purpose. It is possible to integrate APM as a module of our assessment means. Its output can be automatically used for the next steps.

APM is integrated in a few software. Initially, APM gives only the result of calculations of different propagation models. It does not visualise its result. Also APM has not any GUI. That makes the understanding of APM relatively hard, especially at the beginning. At the same time the lack of GUI is the reason why we can adapt APM to our needs either we want to use GUI or not. There are some successful examples of the visualisation of APM - AREPS and TEMPER. These programs make calculations using APM. It is easy and clear for user to enter input parameters. AREPS, for example, offers the statistical data for almost every place of the Earth about air temperature, refractivity profile depending on the time of the year, the possibility to read the standardised data about the terrain and weather, etc. The program has the other tools, which makes the work with APM much easier: the possibility to operate with different projects, to work with the table information, etc. For the user it is more comfortable than the APM source code. Thales, for example, uses AREPS during some projects.

ST&I works with APM version 1.3.5. There are two subversions, which differ only in structure of their functions. The first one consists of 53 files: 51 functions, 1 main program and 1 module. The second version consists of 3 files (apmmain.f90, apmsubs.f90, apm_mod.f90), where these 51 functions (subroutines) are combined in one file - apmsubs.f90. Apmmain.f90 starts the program using the variables defined in apm_mod.f90. Apmsubs.f90 has all the functions to compute different propagation models (FE, RO, PE and XO). The APM metrics is shown in Table 3.1.
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| Classes       | 0 |
|---------------|---|
| Files         | 3 |
| Library Units | 53|
| Lines         | 10121|
| Lines Blank   | 2506|
| Lines Code    | 4184|
| Lines Comment | 3587|
| Lines Inactive| 0 |
| Executable Statements | 4188 |
| Declarative Statements | 390 |
| Ratio Comment/Code | 0.86 |

Table 3.1: APM metrics

The program reads external file with input parameters (in our case file.in, see Algorithm 3.1) and creates an output file as a result (file.out, see Algorithm 3.2).

Algorithm 3.1 Fragment of the APM input file

```
2800. :Frequency in MHz
20. :Antenna height in m
1 :Antenna type (1=OMNI,2=GAUSS,3=SINC(X),4=COSSEC2,5=HTFIND,6=USRHTFIND,7=USRDEF)
0 :Polarization (0=HOR,1=VER)
0. :Beam width in deg (this value is ignored for OMNI and USRDEF antenna)
0. :Antenna elevation angle in deg(this value is ignored for OMNI and USRDEF antenna)
0 :Number of cut-back angles and factors (used for specific height-finder antenna)
0. :Minimum output height in m
100. :Maximum output height in m
1. :Maximum output range in km
5 :Number of output height points
100 :Number of output range points
0 :Extrapolation flag
0. :Surface absolute humidity in g/m3
0. :Surface air temperature in degrees
0. :Gaseous absorption attenuation rate in dB/km
0 :Number of wind speeds/ranges specified
1 :Number of refractivity profiles
1 :Number of levels in refractivity profiles
0. :Range of first refractivity profile in km
209.2 : Height & M-unit value of ref. profile 1, level 1
1 :Number of ground composition types
0., 0., 0. : Range (km), ground type (integer), permittivity, conductivity
0 : Number of terrain range/height points
```
Algorithm 3.2 Fragment of the APM output file

********Output Loss and Prop. Factor Values*******

range in km = 0.05
Height(m) Loss(dB) PFac(dB)
20.00 67.80  -2.20
40.00 65.70  0.40
60.00 85.50 -17.80
80.00 69.10  0.20
100.00 78.70 -7.70

range in km = 0.10
Height(m) Loss(dB) PFac(dB)
20.00 73.70  -2.10
40.00 82.30 -10.60
60.00 74.60 -2.40
80.00 67.30  5.40
100.00 68.10  5.50

As a tool APM can be the part of the assessment means. It computes the pattern propagation factor in the space between the source (radar) and the wind farm.

When APM is launched, it reads the input file, makes the calculations and writes the output file with initial parameters and the final result. The result consists of the propagation factor and loss at the range, height and resolution we want. For our needs we use only the information about propagation factor.

In order to operate with the output of APM we need to create the tool that will read and visualise propagation factor. Also it should prepare the right format of data for the next steps, for example, to compute RCS of wind turbine. Regarding the idea to automate the algorithm of assessment means, we have chosen Matlab.

The main script makes a few steps:

1. Read an external data about the terrain of the wind farm area (profiles of each wind turbine), an antenna pattern, refractivity profiles,
2. Run the APM code written in Fortran.
3. Read the APM output.
4. Visualisation.
5. Create the readable file for the RCS program.

We decide to run APM from Matlab environment (the second step). In fact, there are two ways to do that. Matlab lets create special *mex* file that runs as its function. This file could be generated running the compiled code of Fortran 90 by a special function of Matlab. This solution was applied in ST&I by another intern [27]. However, the generated file operates only in the OS where it was created. Another way is the possibility to use the OS command line from Matlab. It means that we can compile and run APM directly from the script or function. At the same time the performance of Fortran 90 code is high. The difference between two variants to run APM under Matlab is shown in Figure 3.1.
Steps 3 works with file.out (Algorithm 3.2). Matlab script loads this file and retrieves the PPF data. Afterwards it stacks the information for the further visualisation. As a result of the 4th step we receive the image like Figure 3.2. Here the abscissa and ordinate are the range and height respectively. The colour bar refers to PPF.

3.2.2 CAD Model of the Wind Turbine

In spite of the fact that the most precise model of a wind turbine can be given only by its producer, we also can build such a model based on specifications of the machine. The point is that some critical parts of wind turbines are more or less standardised. Thus, the overall dimensions and the dimensions of the nacelle are given in specifications. The blade design can be found in the wind turbine airfoil catalogue[9] according to its identification number.

Therefore, we are able to collect from Internet the basis of information. Afterwards the reflectivity of the turbine can be analysed basing on a few elements (Table 3.2).

| External surface                  | Spar                          | Lightning protection                              |
|-----------------------------------|-------------------------------|---------------------------------------------------|
| 2 shells (internal/external)      | More stronger material than shell material | Conductor wire at least 40 mm²                     |
| Variable thickness                | Rectangular section and filleted edges | With or without conductor shell at blade tip      |
| Fibre reinforced composite material | Association with shell transmission loss (D/R) | Association with shell transmission loss (D/R)     |

Table 3.2: Estimation of wind turbine materials

When a data about the turbine is known, we can design its CAD model (Figure 3.3). For this step we use Rhinoceros NURBS CAD software.
In order to use CAD model for RCS computations it is necessary to transform the data to another format. The code has the capability to move the rotor (hub+blades) step by step, to change the pitches of the blades and if needed also to orientate the nacelle in azimuth.

### 3.2.3 Radar Cross Section

According to the IEEE dictionary of electrical and electronics terms \[24\], RCS is a measure of reflective strength of a target defined as \( 4\pi \) times the ratio of the power per unit solid scattered in a specified direction. More precisely, it is the limit of that ratio as the distance from the scatterer to the point, where the scattered power is measured approaches infinity \[25\]:

\[
\sigma = \lim_{r \to \infty} \frac{4\pi r^2 |E_{\text{scat}}|^2}{|E_{\text{inc}}|^2}
\]  

(3.1)

where

\( E_{\text{scat}} \) and \( E_{\text{inc}} \) - the scattered electric field and the field incident at the target respectively

ALBEDO is the code used at Thales Air Systems in ST&I in high frequency domain. It computes RCS and can run other software that rotate objects. In this case RCS can be computed as a function of:

- angles \( \theta \) and \( \varphi \) in wind turbine axis system;
- radar frequency (S band);
- position of the rotor: 8831 angles (1/3 of the round);
- pitch law: typical blade pitch fixed angles.

The code retrieves a polynomial surface from the file of ALBEDO format. After ALBEDO analyses the surface in order to automatically find corner reflectors and isolated areas. The code carries out the reflection of the surface C1 (approximation using a physical optics). Also it takes into account moving parts (the rotor of a helicopter, the screw propeller) by means of mixed method driven by Generalised Ray Expansion (GRE).

As a result ALBEDO gives tables with complex coefficients of the matrix D associated with input position parameters. The output can be presented in Matlab format.

### 3.2.4 ASTRAD Module

Architecture and Simulation Tool for Radar Analysis and Design (ASTRAD) - or Atelier de Simulations Techniques Radars & Auto-Directeurs in French - \[22\] is a software developed at Thales Air Systems.

The ASTRAD project was launched in 2002 for a four-year period of development, with a release of its first version by mid-2006. Initially the decision to design ASTRAD was taken by French MoD and Thales group.

The ASTRAD software stands as a fully integrated development environment (IDE) aiming at:

- Proposing built-in solution, to create and run complex systems simulations for the full benefit of system designers and operational end users.
- Providing a framework with libraries and complete applications to internal and external partners, giving them the opportunity to focus on their own added value,
- Promoting innovation and cooperation within a community (Agencies, Laboratories, Industries) in accordance with Intellectual Properties Rules.
The ASTRAD platform can accommodate a wide range of computer and scientific languages in a single simulation and that is exactly what we need for our project. For instance, we use APM written in Fortran 90, RCS simulation coded in C++ and middleware runs under Matlab.

ASTRAD may be used for the different steps of the development path. Up to now, ASTRAD supports many computer languages like C / C++, Java and Fortran 90 and scientific suites like Matlab and PV-Wave.

The default library (Figure 3.4) results from the effort of a large panel of experts. It gathers a quite extended, yet manageable, set of data types sufficient for a large majority of radar developments. If needed, each user is entrusted the right to modify those types or create a new base for his own interest. Regarding our project the problem concerns the propagation module marked in red. In the next Section 3.3 we use the data from Radar description that goes to Environment block.

Thales Air Systems operates ASTRAD in several ways:

- **Upstream studies**: ASTRAD simulations are exploited to define and validate future radar time management concepts or Non-Cooperative Target Recognition processes.
- **Proposal**: ASTRAD is used to evaluate radar performance (coverage, accuracy, discrimination, etc.) in complex environment (clutter, jammer, etc.) against several target types (aircraft, cruise missile, helicopter, etc.).
- **Design**: ASTRAD is used to define innovative Signal Processing Building Blocks of the Thales surface radar family.
- **Validation**: a specific Analysis tool of Integration Verification Validation and Qualification has been developed and deployed. A current application is radar parameter tuning before the acceptance test.

This report concerns the proposal and design. On one hand the assessment of the wind farm impact on the radar deals with new environment and with radar performance in this environment. On the other hand the solution concerns the Signal Processing Building Block for the radar STAR 2000.

### 3.3 Solution

The solution consists in method that uses described tools. As a result, we need to know the wind farm impact in terms of RCS. This data should be based on the information about the radar, environment and wind farm.

If the objective is to choose the place to maintain the wind farm or the radar, it is necessary to find the place, where turbines will make the least impact on the radar. The further explanation is given for the case when the place of the radar is known and we evaluate the disposition of the wind farm. If we would examine the disposition of the radar, the idea of an algorithm remains the same. The solution presents the following algorithm:

1. Collect all the necessary data for further steps (Table 3.3).
2. Define the possible disposition of the wind farm or radar.

3. Compute an electromagnetic field in the area of every turbine for the height from the surface up to its top. APM is used for this step, though it calculates only the amplitude. In Chapter 4 we give the solution to calculate the complex field that includes the phase as well.

4. Simulate RCS.

5. Choose the disposition of the wind farm, where its influence on the radar is minimal.

The example of this algorithm is given in Chapter 5. Usually each wind farm is visible by radars using different wavelengths and operation in different places. Despite possible solution for one radar, it can be unfit for others or even makes worse. Nevertheless, the common solution is to place the farm between the hills, where it is more or less invisible for radars.

This algorithms could be implemented by the tool ASTRAD shown in Subsection 3.2.4.

In order to make things clearer Figure 3.5 shows the scheme of the process.

| Radar                  | Environment                      | Wind farm                  |
|------------------------|----------------------------------|----------------------------|
| Frequency              | Terrain profile                  | Number of turbines         |
| Antenna height         | Reflectivity of the surface      | Height of turbines         |
| Polarization           | Refractivity profiles            | Length of blades           |
| Antenna elevation angle| Surface air temperature          | Type of the airfoil        |
|                        | Windspeed                        | Revolution speed           |
|                        | Gaseous absorption               | Number of blades           |
|                        | Surface absolute humidity        | Angles relative to the radar|

Table 3.3: Input data
Figure 3.5: Diagram of the algorithm
Chapter 4

Complex Pattern Propagation Factor

4.1 Introduction

In Subsection 3.2.1 we examined APM as a tool. In this Chapter we always deal with APM.

First of all one must say why we pay attention to the complex PPF. By default APM calculates PPF based on the amplitude and it does not take into account the phase of the wave. This is critical for the next tool of assessment means - RCS (see Subsection 3.2.3) because in order to calculate RCS we need to have both an amplitude and a phase of the electromagnetic wave. Having the source code of APM we can understand its calculations and change the code in order to have the necessary phase.

APM consists of four different propagation models - Flat Earth (FE), Ray Optics (RO), Extended Optics (XO) and Parabolic Equations. APM automatically calculates bounders of each model in the space and performs them. However, there are only two models, which give PPF at low heights - FE and PE. Therefore, it’s obvious that the study of these two models is sufficient within the framework of wind farm context. Close to the surface FE works on the distance less than 2.5 km, while PE covers further ranges. Typical boundaries of APM models are presented in Figure 4.1, where the yellow field - FE, brown - RO, blue - PE and light blue - XO. Disposition of boundaries depends on input parameters.

![Figure 4.1: Zones of APM](image)

The principium of FE and RO is the same. It consists in the definition of direct and reflected rays in each point of space. FE is simpler than RO. In comparison with FE, RO uses more input parameters: the refraction, terrain profile and some others. The conductivity and permittivity of the terrain are taken into account in both models. Two models have been validated by the evaluation of every step of the APM code. Finally, the phase PPF was found.

The critical model, responsible for the propagation in the wind farm area, is PE. The operation of PE differs completely from FE and RO and is shown in details below.

The last model, XO, is the least precise. In fact, it uses the upper layer of PE field and interpolates it to the top according to the refraction profile. XO does not participate in propagation close to the surface. This model is not considered here in details because it is useless for the wind farm problem.

The module PE is examined in details because practically it covers all ranges, where wind farms operates.
4.2 Formulaic Definition

In order to define the pattern propagation factor we cite the Radar Handbook of Merrill Skolnik [33]. According to the classical mathematical definition the pattern propagation factor, for a point in space at a range $R$ and elevation angle $\theta$, is the magnitude of the ratio of the electric field strength $E(R, \theta)$ at that point (e.g., volts per meter) to the field strength that would exist at the same range in free space and in the antenna beam maximum (eqn. 4.1).

$$ F(R, \theta) = \frac{E(R, \theta)}{E_0(R)} \quad (4.1) $$

where

$E_0(R)$ - the beam-maximum free-space field strength at range $R$

To solve any reflection-interference problem, it is necessary to know the value of the specular-reflection coefficient $\Gamma$ of the surface and the characteristics of the vertical-plane antenna pattern, expressed as a pattern factor. The reflection coefficient is a complex number of magnitude $\rho$ and the phase angle $\phi$. Similarly the pattern factor, a function of the vertical-plane angle $\theta$, has a magnitude $|f(\theta)|$ and a phase angle $\beta$. In terms of these quantities, the general formula of $F$ when multipath interference occurs is

$$ F = |f_d + \rho f_r e^{-j\alpha}| \quad (4.2) $$

where

$f_d$ and $f_r$ - the magnitude of $f(\theta_d)$ and $f(\theta_r)$ respectively

$\alpha$ - the total phase difference of the direct and reflected waves at their point of superposition, i.e., at the target of the transmitted waves and at the receiving antenna for the returned echo

This total phase difference is the resultant of the phase difference $(\beta_r - \beta_d)$ of the pattern factors, the phase shift $\phi$ that occurs in the reflection process, and the phase difference due to the path-length difference. The absolute-value brackets indicate that $F$ is a real number, although the reflection coefficient $\Gamma$ and the pattern factor $f(\theta)$ are in general complex.

The propagation factor $F$ is often expressed in dB [26]. If we approximate the distance $d$ between the terminals by range $x$, we get eqn. 4.3

$$ F(x, z) = 20 \log |u(x, z)| - 10 \log(x) - 10 \log(\lambda) \quad (4.3) $$

where

$x$ - range
$z$ - height
$u$ - complex field

Anticipating things, one must say that the FE and RO use the total phase difference as it is pointed out in eqn. 4.2. The phase difference means the relative phase. In order to compute RCS we need to have the absolute one.

On the other hand, the PE and XO calculate PPF using eqn. 4.3. Moreover, $u$ contains the information about the phase.

The next section shows how to retrieve the absolute phase from important models of APM.

4.3 Extraction from Advanced Propagation Model

4.3.1 Flat Earth

FE represents the simplified geometric model of a ray propagation and its application has some limitations. FE operates in area, where antenna elevation angles above 5 degrees or ranges less than approximately 2.5 km (see Figure 4.1, the yellow field). As follows from the term “Flat earth”, the model works only in the space above the flat terrain. Otherwise it would compute the propagation with marked errors. As a simple model FE does not take into account many input parameters of APM, for example, the refractivity profile. However this simplification has a reason. FE operates in a relatively small space, where the effect of a refraction does not play a big role. Also the model ignores surface effects that deviate a ray during reflection.

There are always two rays - direct and reflected. The model is shown in Figure 4.2.
From the two path lengths \( r_1 \) and \( r_2 \), the surface-reflection phase lag angle \( \varphi \), and the free-space wave number \( k_0 \), the total phase angle is determined as:

\[
\Omega = (r_1 - r_2)k_0 + \varphi
\]  

(4.4)

The planar travelling wave solution of the wave equations is:

\[
E(r) = E_0 e^{i\varphi}
\]  

(4.5)

The electromagnetic field of some point of the space (index \( p \)) is a superposition of the direct and reflected waves (index \( d \) and \( r \) respectively):

\[
E_p e^{i\varphi_p} = E_d e^{i\varphi_d} + E_r e^{i\varphi_r}
\]  

(4.6)

\( E_d \) and \( E_r \) are determined according to the antenna pattern factor of \( \alpha_d \) and \( \alpha_r \).

In order to compute the resultant amplitude it is enough to know the phase difference \( \Omega \):

\[
|E_p e^{i\varphi_p}|^2 = E_d^2 + E_r^2 + 2E_dE_r \cos \Omega
\]  

(4.7)

However, still we do not know the absolute resultant phase \( \alpha_p \). To retrieve the phase we can use:

\[
\varphi_p = \arctan \left( \frac{E_d e^{i\varphi_d} + E_r e^{i(r_2k_0 + \Omega)}}{E_d e^{i\varphi_d} + E_r e^{i(r_2k_0 + \Omega)}} \right)
\]  

(4.8)

Eqn. 4.7 is used by APM to calculate the propagation factor. It does not operate with absolute phase that needed for complex pattern propagation factor. With eqn. 4.8 we have both an amplitude and phase. Than it is possible to compute the complex pattern propagation factor.

The APM subroutine that calculates FE is called \( \text{fem} \). In terms of a code the solution is given in Algorithm 4.1.

**Algorithm 4.1 Phase of the Flat Earth model**

```plaintext
! Now get total phase lag and compute propagation factor and loss.
phdif = (r2 - r1) * fko + rphase
frterm = facr * rmag
ffac2 = facd*facd + frterm*frterm + 2. * facd * frterm * dcos(phdif)

!Added code begins
ffac2 = atan(aimag(facd*exp(qi*r1*fko)+frterm*exp(qi*(r2*fko + rphase)) ,
real(facd*exp(qi*r1*fko)+frterm*exp(qi*(r2*fko + rphase)))))
!Added code ends
```

where
The application of FE in our study is very limited. We mentioned that APM uses FE only for short distances - 2.5 km and less. In reality there are no wind turbines situated very close to the radar. But still if we deals with such a situation, PE cannot give us the satisfactory result. By the way, this is one of the reasons why APM does not use only PE - it does not work for the short range.

4.3.2 Ray Optics

Basically RO is quite similar to FE but has a few qualitative differences. Within the RO region (see Figure 4.1, the brown field), the propagation factor is calculated from the mutual interference between direct-path and surface-reflected ray components using the refractivity profile at a zero range. Full account is given to focusing or defocusing along both direct and reflected ray paths and to the integrated optical path length difference between the two ray paths, to give precise phase difference, and, hence, accurate coherent sums for the computation of propagation loss [8]. It means that in comparison with FE, RO considers the terrain, refractivity profile (partly), parameters of the surface, etc. That makes RO computations more complicated. RO still does not concern the effect of the diffraction.

![Figure 4.3: RO ray tracing](image)

RO seems to be useless for our purposes because it does not compute the field close to the surface. There are two main subroutines in APM that compute a propagation factor. Rocalc provides characteristics of direct and reflected rays. And roloss calculates the final field using the result of rocalc and stores propagation factor.

4.3.3 Parabolic Equations

4.3.3.1 Theory of PE

Theory of parabolic equations is perfectly described in [26]. We cite a few basic ideas from this book about the theory, which will help us to understand how PE operates in APM.

The propagation of electromagnetic field is associated with the paraxial direction $x$:

$$u(x, z) = e^{-ikx}\psi(x, z)$$  \hspace{1cm} (4.9)

The point of using this reduced function is that it is slowly varying in range for energy propagation at angles close to the paraxial direction, which gives it convenient numerical properties.

The scalar wave equation in terms of $u$ is:

$$\frac{\partial^2 u}{\partial x^2} + 2ik\frac{\partial u}{\partial x} + \frac{\partial^2 u}{\partial z^2} + k^2(n^2 - 1)u = 0$$  \hspace{1cm} (4.10)

This can be formally factored as:

$$\left\{ \frac{\partial}{\partial x} + ik(1 - Q) \right\} \left\{ \frac{\partial}{\partial x} + ik(1 + Q) \right\} u = 0$$  \hspace{1cm} (4.11)

where the pseudo-differential operator $Q$ is defined by:
CHAPTER 4. COMPLEX PATTERN PROPAGATION FACTOR

\[ Q = \sqrt{\frac{1}{k} \frac{\partial^2}{\partial z^2} + n^2(x, z)} \]  
(4.12)

Pseudo-differential operators are constructed from partial derivatives and ordinary functions of the variables. A formal mathematical framework is required to give a precise meaning of the square-root symbol in the expression of \( Q \). The square root corresponds to the composition of operators, in the sense that:

\[ Q(Q(u)) = \frac{1}{k^2} \frac{\partial^2 u}{\partial z^2} + n^2 u \]  
(4.13)

must be satisfied for all functions \( u \) in a certain class. The construction of the appropriate square-root symbol is linked to the class of functions \( u \) on which it operates, and this in turn depends on the boundary conditions for the partial differential equations given by eqn. 4.10. More generally, we shall assume that \( Q \) can be defined unambiguously and that expansions for the ordinary square root function can be applied to \( Q \).

There are errors inherent in the factorisation given in eqn. 4.11: if the refractive index \( n \) varies with range \( x \), the operator \( Q \) does not commute with the range derivative and the factorisation is incorrect. Hence some care must be taken in the applications to make sure that the resulting error remains small.

The next step is to split the wave equation into the two terms defined by eqn. 4.11 and to look at functions satisfying one of the resulting pseudo-differential equations:

\[ \frac{\partial u}{\partial x} = -ik(1 - Q)u \]  
(4.14)

\[ \frac{\partial u}{\partial x} = -ik(1 + Q)u \]  
(4.15)

Eqns. 4.14 and 4.15 correspond respectively to forward and back propagation waves. In a ray picture, forward propagation corresponds to rays propagating with increasing \( x \), and back forward propagation to rays propagating with decreasing \( x \). Eqns. 4.14 and 4.15 are the outgoing and incoming parabolic wave equations.

In a range-independent medium, where there are communicator problems with the factorisation of eqn. 4.11 a solution of either eqn. 4.14 or 4.15 will automatically satisfy the original reduced wave equation, eqn. 4.10. However such a solution does not in general correspond to the actual electromagnetic field. For example a solution of the outgoing eqn. 4.14 neglects the backscattered field. In order to get exact solution of eqn. 4.10 eqns. 4.14 and 4.15 should be solved simultaneously in the coupled system:

\[
\begin{align*}
    u &= u_+ + u_- \\
    \frac{\partial u_+}{\partial x} &= -ik(1 - Q)u_+ \\
    \frac{\partial u_-}{\partial x} &= -ik(1 - Q)u_- 
\end{align*}
\]  
(4.16)

The approximation we make by solving for each term separately is a paraxial approximation: for example, for the outgoing parabolic wave equation, we solve for energy propagating in a paraxial cone centred on the positive \( x \)-direction.

Eqns. 4.14 and 4.15 are pseudo-differential equations of first order in \( x \) (hence the “parabolic” terminology). They can be solved by marching techniques, given in the field of the initial vertical and the boundary conditions at the top and the bottom of the domain. The outgoing parabolic wave equation, eqn. 4.14 has the formal solution:

\[ u(x + \Delta x, \cdot) = e^{ik\Delta x(-1+Q)}u(x, \cdot) \]  
(4.17)

The forward propagation field is obtained at a given range from the field at a previous range, and appropriate boundary conditions at the top and bottom of the domain, in other words the solution is marched in range. The computation gain is substantial compared to the elliptic wave equation, which is of second order in both \( x \) and \( z \) and must be solved simultaneously at all points of the integration domain.

The splitting of the wave equation into two paraxial terms implies that only energy propagating inside a paraxial cone can be modelled. This limits the type of propagation which can be represented accurately. However the paraxial representation is very accurate for a number of problems and also has substantial computational advantages.

The PE derived in this section provides a paraxial approximation of the two-dimensional scalar wave equation. Naturally the scalar framework is no longer adequate for general three-dimensional problems, where polarisation aspects require a vector description. In that case scalar PE have to be written for
the electromagnetic field components and coupled through boundary conditions at interfaces and the divergence-free conditions.

It is useful to look through a staircase terrain modelling. The theory of this model is applied in APM. Let the terrain is represented as a sequence of linear segments. The coordinate system measures height from the terrain. In other words we define new range and height variables by:

\[
\begin{aligned}
\xi &= x \\
\zeta &= z - h(x)
\end{aligned}
\]  

(4.18)

where

\[h(x)\] - terrain height

Assume the terrain has slope \(\alpha\) on segment \(x_1 \leq x \leq x_2\). Then we have in the corresponding vertical slice:

\[
\begin{aligned}
\xi &= x \\
\zeta &= z - h(x_1) - \alpha(x - x_1)
\end{aligned}
\]  

(4.19)

We now look at the new function \(\nu\) defined by

\[
\nu(\xi, \zeta) = e^{ik\alpha\zeta}u(x, z)
\]

(4.20)

This function compensates for the wavefront shift relative to the terrain. We have:

\[
\begin{aligned}
\frac{\partial \nu}{\partial \xi} &= e^{ik\alpha\zeta} \left\{ \frac{\partial u}{\partial \xi} - \alpha \frac{\partial u}{\partial \zeta} \right\} \\
\frac{\partial \nu}{\partial \zeta} &= e^{ik\alpha\zeta} \left\{ \frac{\partial u}{\partial \zeta} + ik\alpha u \right\} \\
\frac{\partial^2 \nu}{\partial \zeta^2} &= e^{ik\alpha\zeta} \left\{ \frac{\partial^2 u}{\partial \zeta^2} + 2ik\alpha u \right\}
\end{aligned}
\]  

(4.21)

Hence the standard PE becomes in terms of \(\nu\):

\[
\frac{\partial^2 \nu}{\partial \zeta^2} + 2ik \frac{\partial \nu}{\partial \zeta} + k^2(n^2 - 1) \nu = 0
\]

(4.22)

We are back to the usual PE, but we now solve for a function which follows the terrain by applying appropriate angle shifts on successive segments. Implementation with a sine transform is straightforward.

As a result the vertical grid resolution can increase substantially.

1. First we shift the wave front, putting

\[
\nu_m(r_{m-1}, \zeta) = u(r_{m-1}, h_{m-1} + \zeta)e^{-ik\alpha_m\zeta}
\]

(4.23)

2. We now propagate \(\nu_m\) to range \(r_m\) using the sine transform method. On interval \([r_{m-1}, r_m]\), the standard PE algorithm is given by:

\[
\nu_m(\xi + \Delta \xi, \zeta) = e^{-ik(\alpha_m^2 - \alpha^2)\frac{\Delta \xi}{2}} S^{-1} \left\{ e^{-2ik\alpha^2\frac{\Delta \zeta}{2}} S \left\{ \nu_m(x_i, \zeta') \right\} \right\}
\]

(4.24)

This propagates the field along the \(m\)th segment, automatically enforcing the boundary condition that the field should be zero at the ground.

3. At range \(r_m\) we go back to \(u\) with the formula:

\[
u_m(r_m, h_m + \zeta) = \nu_m(r_m, \zeta)e^{ik\alpha_m\zeta}
\]

(4.25)

4. To continue the process, we shift the wave front again. In terms of \(\nu_m\), the next function \(\nu_{m+1}\) is given by:

\[
\nu_{m+1}(r_m, h_m + \zeta) = \nu_m(r_m, \zeta)e^{ik(\alpha_m - \alpha_{m+1})\zeta}
\]

(4.26)

Propagation angles are now measured relative to the sloping terrain in each successive slice. From eqn. 4.20 we see that if we want the solution \(u\) to represent propagation angles up to \(\theta_{\text{max}}\) accurately, then \(\nu\) must represent propagation angles up to \(\theta_{\text{max}} + \alpha_{\text{max}}\) where \(\alpha_{\text{max}}\) is the maximum terrain slope modulus. As a result the vertical grid resolution can increase substantially.

This algorithm is applied in APM. The idea is that if we can completely understand how PE operates in APM, we can clearly define the phase and retrieve the necessary data. In our case this is the phase of electromagnetic wave.
4.3.3.2 PE in APM

In APM PE can be chosen for all the space. This mode is called “PE only”. We use this to analyze PE model. According to the code, APM divides the space into vertical layers. The one dimension matrix corresponds to each vertical layer. This vector contains the field from zero to the maximum height. At every step, APM propagates the previous layer to the next range taking into account the refractivity and terrain profile.

Firstly, APM starts a module computing the first layer at a zero distance for all heights (eqn. 4.27). The subroutine of APM, responsible for these calculation, is called \textit{xyinit}.

\[
U_j = c_a s_{gain} \left[ f(\alpha_d) e^{-ip_j \text{ant}_0} - f(-\alpha_d) e^{ip_j \text{ant}_0} \right], \quad H \text{pol}
\]

\[
U_j = c_a s_{gain} \left[ f(\alpha_d) e^{-ip_j \text{ant}_0} + f(-\alpha_d) e^{ip_j \text{ant}_0} \right], \quad V \text{pol}
\]

\[
\alpha_d = \arcsin(p_j)
\]

\[
c_a = (1 - p_j^2)^{3/4}
\]

where \(s_{gain} = \sqrt{\lambda/z_{max}}\) - the normalisation factor, where \(\lambda\) - wavelength, \(z_{max}\) - total height,

\(\alpha_d\) and \(-\alpha_d\) - the antenna pattern factors for the direct path and for the reflected path,

\(p_j = j\Delta \theta\) - where \(\Delta \theta\) - the angle difference between mesh points in p-space, \(j\) - index from 0 to transform size,

\(\text{ant}_0 = k_0 \text{ant}_{ht}\) - a height-gain value at the source, where \(\text{ant}_{ht}\) is the transmitting antenna height above the local ground, \(k_0\) - wave number,

\(i\) - imaginary unit

The free-space propagator phase array is defined as well. It is calculated once and will be used to propagate every further layer (eqn. 4.28).

\[
frsp_{pj} = f_{norm} e^{i\Delta r_{PE} (\sqrt{k_0 - (j\Delta p)^2} - k_0)}
\]

where

\(f_{norm}\) - the Fourier transform normalisation constant,

\(\Delta r_{PE}\) - PE range step,

\(\Delta p = \pi/z_{max}\) - the angle (or p-space) mesh size.

After the first layer has been initialised, the propagation begins for the next one. A current layer is assigned as a previous one. The purpose of the next step is to propagate a complex PE solution in a free space by a one range step. Upon entry the PE field is transformed to the p-space (Fourier space) and its array elements are multiplied by corresponding elements in the free-space propagator array given by eqn. 4.28. Finally, the PE field is transformed back to a z-space.

After the free-space propagation, an information about terrain profile is used. This step is quite simple. The PE field is shifted up or down at the difference in heights between current and previous ranges.

Finally, the field is multiplied by a function, based on the refractivity profile, and given by eqn. 4.29.

\[
U = U e^{i\Delta r \text{prof}_\text{int}}
\]

\text{Profint} is a one dimension matrix that presents the refraction from zero to maximum height. This is an interpolated original refraction multiplied by a wave number.

Besides these critical steps there is a number of sub-functions, which generally deal with input parameters: there are some differences in the algorithm for V and H polarisation, for different antenna types, for the presence of wind, air temperature, the Earth flattering transformation takes place, etc. However, the main algorithm remains the same.

Considering our goal, there are critical steps in the PPF computation that were analysed with both visualisation and explanation.

In Figure 4.4 one can see the influence of the refraction of non-isotropic space in comparison with the free space. There are two ways to prove that the PE field does not take into account the ray trace and differs from FE and RO:
1. Check the code in order to find calculations concerning the ray trace.

2. Change input parameters to see the influence in an output.

To the first point, the PE source code with its subroutines does not have functions performing the ray trace.

Concerning the second point, one can show the influence of the refraction playing with input parameters. The terrain has the same height (50 m) and same conductivity and permittivity for every example. Results show that the difference is only due to the \( \text{profint} \) matrix - the refraction of space (eqn. 4.29), especially it is clear with the duct effect\(^1\) (Figure 4.4c).

![Figure 4.4: PPF](image)

(a) Isotropic space  
(b) Non-isotropic space  
(c) Non-isotropic space, duct effect

The refraction of these examples is given in Table 4.1.

| Height, m | Isotropic, \( M \)-unit | Non-isotropic, \( M \)-unit | Non-isotropic, duct effect, \( M \)-unit |
|-----------|--------------------------|-----------------------------|-------------------------------------|
| 0         | 330                      | 330                         | 330                                 |
| 100       | 330                      | 430                         | 370 (300 m)                         |
| 230       | 330                      | 530                         | 320 (400 m)                         |
| 2000      | 330                      | 630                         | 500                                 |

Table 4.1: Refraction of isotropic and non-isotropic spaces

Moreover, the parameters of terrain such as conductivity and permittivity do not impact on the propagation. These parameters do not participate in calculations, and we will receive the same PPF with different values.

In the presence of terrain, initially, APM sets the height of the current layer to zero even if there is the altitude. The current layer is assumed as a previous one. Subsequently, APM applies a free-space propagation. Then the result is shifted according to the terrain height derivative. Finally, the refraction is considered.

![Figure 4.5: Influence of the terrain](image)

(a) Free space  
(b) With the terrain, “shift” function commented  
(c) Final result of APM

Figure 4.5b shows PPF calculated without the shift (the code was commented). One can see that the field on the terrain in Figure 4.5b is the same as in Figure 4.5a and almost the same as in Figure 4.5c.

\(^1\)Example from p. 90, Levy, M., Parabolic Equation Methods for Electromagnetic Wave Propagation, IEE, London, UK (2000).
4.5c but shifted down by the height of this terrain. Nevertheless, there is an important difference (Figure 4.5b - 4.5c). As a matter of fact, the current layer, based on the field of previous one (which contains the terrain), is multiplied by a free-space propagator (see eqn. 4.28), which initially does not have the terrain data. It leads to the final result that presents an effect of diffraction as shown in Figure 4.5c.

Logically and mathematically this algorithm is presented in a literature and shown in Subsubsection 4.3.3.1.

In contrast to other models of APM, PE exactly loses the phase when calculates PPF, while other models do not calculate the phase at all. It means that, during calculations, APM operates with PE field, which is the array of complex numbers. In order to compute PPF, it takes the absolute value (magnitude) of the complex field (eqn. 4.30), interpolating it afterwards.

\[ U = |U| \] (4.30)

Finally, APM calculates the pattern propagation factor using the usual known equation, presented in different publications (eqn. 4.31).

\[ F_{dB} = 20 \log U + 10 \log r \] (4.31)

where

\[ r \] - range where \( U \) is calculated

Thus, one can easily retrieve the phase of PE field before the magnitude is computed (eqn. 4.30). This phase is the angle between real and imaginary part of \( U \). There should be eqn. 4.32 instead of eqn. 4.31 in APM source code:

\[ P = \arctan \left( \frac{\Im(U)}{\Re(U)} \right) \] (4.32)

where

\[ \Im(U) \] and \( \Re(U) \) - imaginary and real parts of \( U = \Re + i\Im \) respectively

In that way \( P \) and \( F_{dB} \) have the same resolution and dimension that gives us the phase and amplitude of exactly the same point of space.

At the level of the code the solution is given in Algorithm 4.2.

Algorithm 4.2 Phase of the Parabolic Equations

\begin{verbatim}
u0 = u(nb)
u1 = u(nbp1)

pmag0 = abs(u0)

pmag1 = abs(u1)

pmag = pmag0 + fr * (pmag1 - pmag0)

pmag = dmax1( pmag, pmagmin )

getpfac = 20.*dlog10( pmag ) + rlog

!Added code begins

getpfac = pmag !This is an amplitude of complex field

getpfac = atan2( aimag(u0 + fr * (u1 - u0)), real(u0 + fr * (u1 - u0))) !This is a phase of complex field

!Added code ends

where

\[ pmag \] - interpolated magnitude of field
\[ u1 \text{ and } u2 \] - complex field at bin directly below and above desired height
\[ fr \] - interpolation fraction
\[ getpfac \] - amplitude or phase of complex field
\end{verbatim}

There are a few function in APM for PE. The main ones are getpfac and calclos.
4.3.4 Extended Optics

XO performs a ray trace on all rays within one output range step and returns the propagation loss up to the necessary height, storing all angles and heights. It calculates loss values in the height region above the maximum height of the PE model. APM uses only the XO and PE models if the terrain profile is not flat for the first 2.5 km and if the antenna height is less than or equal to 100 m.

XO seems to be useless for our purposes because it does not compute the field close to the surface as well as RO. 

*Ext*, *xemit* and *xostep* are subroutines, which calculate XO.
5.1 Introduction

Previous Chapters give us a methodology. Here we apply the scenario, where the radar operates in the presence of the wind farm. All the data and information are real. Thus, there is an ATC radar STAR-2000, Beinn Tharsuinn wind farm with 17 turbines, and environment in the UK. In Section 5.2 we give the parameters for the further simulation (Section 5.3). In fact the Chapter is based on the solution given in Chapter 3. Finally, we examine different scenarios of the wind farm disposition and give the most suitable for the radar.

5.2 Input Parameters

5.2.1 Wind Farm

For our example we take a real wind farm that runs in United Kingdom. The farm is situated at 32 km from the ATC radar, which operates in the Inverness airport (Figure 5.1). The wind farm is located almost on the top of the Beinn Tharsuinn hill. It means that the farm is good visible from the radar and negatively acts on its signal processing. The common information about this wind farm is given in Subsection 2.2.4 in Table 2.1.

Figure 5.1: Wind farm and Star 2000

The wind farm consists of 17 turbines Vestas V66 (Figure 5.2) [2].
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Figure 5.2: Beinn Tharsuinn farm with 17 wind turbines

Vestas V66 is the model for inland locations (Figure 5.3).

In order to show the possible influence on the radar signal processing we use some technical information about V66 [34] (Table 5.1).

![Figure 5.3: Vestas V66](image)

| Diamater   | 66 m    |
|------------|---------|
| Area swept | 3421 m² |
| Revolution speed | 21.3 rpm |
| Operational interval | 10.5-24.5 rpm |
| Number of blades | 3 |
| Hub height  | 67 m    |
| Total weight| 197 t   |

Table 5.1: Technical information about Vestas V66

One can find the velocity of the blade’s top point at a normal revolution speed (eqn. 1.1):

\[ V = \omega r = 2\pi f r = 2 \cdot \pi \cdot \left( \frac{21.3}{60} \right) \cdot 33 \approx 73.6 \text{m/s} = 265 \text{km/h} \]

The radial airplane speed could be close to the velocity of the blade.

Also dimensions of V66 are comparable with the airplane. Therefore, the value of RCS can have the same order. The design of blades is quite similar to plane’s wings.

For our calculations we take 17 turbines of the Beinn Tharsuinn wind farm. The only data we need are the distance of the wind turbine from the source and its azimuth. It’s enough having coordinates of the radar.
Table 5.2: Parameters of wind turbines

| Wind turbine | Distance, m | Azimuth, ° |
|--------------|-------------|------------|
| 1            | 32262       | -30,769    |
| 2            | 32020       | -30,043    |
| 3            | 32338       | -29,836    |
| 4            | 32583       | -30,188    |
| 5            | 32543       | -30,835    |
| 6            | 32805       | -30,081    |
| 7            | 32656       | -29,633    |
| 8            | 32510       | -29,181    |
| 9            | 32269       | -28,820    |
| 10           | 32520       | -28,812    |
| 11           | 32772       | -28,804    |
| 12           | 32762       | -29,170    |
| 13           | 33050       | -30,426    |
| 14           | 33242       | -30,231    |
| 15           | 32045       | -30,508    |
| 16           | 32332       | -30,207    |
| 17           | 32704       | -30,546    |

5.2.2 Radar

During this study we use the radar of Thales Air Systems STAR 2000 (Figure 5.4a). It is a dedicated, solid-state, modular terminal approach radar, which is suitable for both civilian and military air traffic control applications. The equipment incorporates a dedicated weather channel and its overall range capability can be extended from 60 Nm (111 km) to 90 Nm (167 km) through the use of incremental power increases. STAR 2000 configurations exist for stand-alone, Monopulse Secondary Surveillance Radar (MSSR)/Identification Friend-or-Foe (IFF) associated or Mode S operation with the radar’s data output format being configurable to match all transmission formats [20].

In summary, the main features of STAR 2000 are the following [1]:

- fixed, shelter-mounted and transportable configurations
- full coherence and clutter driven adaptive processing for the improved target detection in severe clutter conditions
- independent dual-polarisation weather channel
- modular, fail-safe, online maintainable, solid-state, frequency diverse/agile transmitter
- digital frequency synthesiser and pulse compression with low time-sidelobes
- auto-adaptive moving target detection with clutter rejection techniques
- false alarm free plot extraction and tracking of up to 1 000 targets
- MSSR/IFF beacon and Mode S reinforcement
- programmable output data formatting
- full built-in test and remote monitoring automatic reconfiguration

The radar operates in the Inverness airport (Figure 5.4b) - an international airport, the main gateway for travellers to the north of Scotland with a wide range of scheduled services throughout the UK and Ireland, and limited charter and freight flights into Europe.
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For our example we have certain parameters of the radar (Table 5.3).

| Parameter            | Value     |
|----------------------|-----------|
| Frequency, MHz       | 2800      |
| Polarization         | Vertical  |
| Antenna height, m    | 15        |
| Latitude             | 52° 32' 48.1" N |
| Longitude            | 4° 03' 25.7" W |

Table 5.3: Parameters of the radar

Figure 5.5 shows normalised antenna pattern. This parameter is used when APM calculates the complex electromagnetic field.

This figure intentionally left blank.

5.2.3 Environment

All the atmospheric data is based on DCS and Sfc data received from AREPS. The statistical information is presented for an average day of July. This data is shown in Table 5.4 and Figure 5.6.
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| Parameter                                      | Value  |
|-----------------------------------------------|--------|
| Surface absolute humidity, g/m²               | 10.55  |
| Surface air temperature, °C                   | 14.6   |
| Gaseous absorption attenuation rate, dB/km    | 0      |
| Windspeed, m/s                                | 6.1    |

Table 5.4: Parameters of the space

![Evaporation duct profile](image1)

Figure 5.6: Evaporation duct profile

Actually, it is possible to receive such an information in real time. There are services that collect, consolidate, perform and offer the data from weather station. Thus, one can make and apply the module that implements this information for needs of this project.

5.3 Implementation

5.3.1 Complex Pattern Propagation Factor

Amplitude is less sensitive to resolution than the phase does. In fact, losses of an amplitude depend on the refractivity profile, presence of the terrain, wind and some others. It changes APPF on relatively big dimensions, which let choose the low resolution.

There are another demands on PPPF. In case of PPPF, the resolution of the space should depend on the frequency of the source. For instance, we deal with relatively small object like a wind turbine. If we have the resolution of APPF less than the dimension of a turbine, we can increase the resolution artificially, interpolating the data. Unfortunately, we can not do that with PPPF, if the initial resolution was less than the dimension of a turbine. According to the Kotelnikov sampling theorem\[1\] we have the discrete frequency of PPPF.

**Theorem 1.** If a function \( z(t) \) contains no frequencies higher than \( B \) hertz, it is completely determined by giving its ordinates at a series of points spaced \( 1/(2B) \) seconds apart.

\[
B < \frac{f_s}{2}
\]  
(5.1)
\[ T \overset{\text{def}}{=} \frac{1}{f_s} \] (5.2)

Fortunately, APM lets receive any resolution and it is defined solely by input parameters. The calculation time increases accordingly.

As the example concerns ATM radars, frequencies of the source lie in band \( S \). Here we use \( f = 2.8 \) GHz that corresponds to \( \lambda \approx 0.1 \text{ m} \). Thus, the resolution of our PPPF should be more than twice \( 0.1 \text{ m} \).

We choose the first turbine to show the complex PPF.

Firstly, we examine APPF. Figure 5.7a shows the propagation of electromagnetic field in terms of an amplitude of the pattern propagation factor. The radar emits from the left and the turbine is situated on the hill on the right. Figure 5.7b presents the APPF, where the turbine operates depending on the height. Its zoomed area is shown in Figure 5.7c. Here, one can see that the resolution chosen for calculation is satisfactory.

\begin{center}
(a) APPF in the direction of turbine 1 (in terms of amplitude), \( dB \)
\end{center}

\begin{center}
(b) Height-APPF of wind turbine 1
\end{center}

\begin{center}
(c) Zoomed area
\end{center}

Figure 5.7: Amplitudes of PPF of wind turbine 1

Now we examine PPPF. Figure 5.8 is similar to Figure 5.7 but shows the phase of an electromagnetic field. The phase is presented in radians.
The Beinn Tharsuinn wind farm has 17 turbines. For every disposition of the turbine we calculate APPF (Figure 5.9) and PPPF (5.10). Finally we are ready to compute the RCS of wind turbine based on the complex pattern propagation factor.
5.3.2 CAD Model of Wind Turbine

As the wind farm consists of turbines Vestas V66, we have to get its CAD model. The most precise model of the wind turbine can be given only by its producer. However, it is possible to make our own turbine, which will be very close to original one. We showed in Subsection 3.2.2 the parts of the turbine are standardised and, using the open information, one can make its model.

The data about V66 have been found from Internet. Basing on this information we create Rhinoceros NURBS CAD model. FFA-W3-211, FFA-W3-241 and FFA-W3-301 airfoil (Figure 5.11) have been successively chosen along the blade axis.

The tower is considered as a truncated cone. The whole model is composed by 51 non-uniform rational B-spline (NURBS) surfaces (Figures 5.12a, 5.12b, 5.12c).
The file with CAD model has been transformed to match with a physical theory of diffraction of ALBEDO's geometrical inputs (a software computing RCS). It is then made of 539 patches.

The turbine is considered as a perfect conductor (Figure 5.12d).

5.3.3 Radar Cross Section

Computations of RCS have been made by the tool shown in Subsection 3.2.3.

Having a 3D CAD model of the wind turbine and knowing an electromagnetic field from its top to the bottom, we can simulate different scenarios of the wind turbine operation. It means we can calculate RCS for any angle of blades and for different position of our radar relative to the turbine. In fact, we deal with three angles and one distance shown in Figure 5.13.
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Figure 5.13: Relative position of the turbine and radar

Vestas V66 has three blades. The angle between them is \( \frac{2\pi}{3} \). It means that turning the turbine has three states equal for the radar. If we consider that initial state is 0 (the blade is aimed vertically upwards) and its full turn is 1, thus one third of the turn is \( \frac{1}{3} \).

For this step we need the complex electromagnetic field depending on the height for certain wind turbine. Therefore, we prepare the data that consists of 1011 points (Algorithm 5.1). Each point is the value of complex field on the different height - HEIGHT (REAL PART, IMAGINARY PART).

Algorithm 5.1 The data of complex field to compute RCS of wind turbine 1

1 1011
-67 ( 0.000000000000 , 0.000000000000 )
-66.9 ( 0.000000000000 , 0.000000000000 )
-66.8 ( 0.000000000000 , 0.000000000000 )
-66.7 ( 0.000000000000 , 0.000000000000 )
-66.6 ( 0.000000000000 , 0.000000000000 )
-66.5 ( 0.000000000000 , 0.000000000000 )
-66.4 ( 0.000000000000 , 0.000000000000 )
-66.3 ( 0.000000000000 , 0.000000000000 )
-66.2 ( 0.000000000000 , 0.000000000000 )
-66.1 ( 0.000000000000 , 0.000000000000 )
-66 ( 0.000000000000 , 0.000000000000 )
-65.9 ( 0.000009153603 , -0.0000326871858 )
-65.8 ( 0.000025242162 , -0.0000335050494 )
-65.7 ( 0.000043548126 , -0.0000343248541 )
-65.6 ( 0.000064158115 , -0.0000351187608 )
-65.5 ( 0.000085202205 , -0.0000356972806 )
...
0 ( 0.002571270631 , -0.003091441143 )
...
33.5 ( 0.0013333934317 , 0.005907384836 )
33.6 ( 0.000574750876 , 0.006025651038 )
33.7 ( -0.000149071504 , 0.006033158599 )
33.8 ( -0.000873455115 , 0.005952254376 )
33.9 ( -0.001583575708 , 0.005812130761 )
34 ( -0.002281865277 , 0.005602097905 )

We assume that the zero point is the nacelle of a turbine. The data is given for the entire turbine and additionally 1 m below and 1.1 m above (Figure 5.14).
Figure 5.15a presents the disposition of the radar relative to the axis of the wind turbine. The wind turbine is situated on the surface on the right of the terrain profile (Figure 5.15b), while the radar is on the left. As we can see the wind turbine operates on the top of the hill. It interferes with the radar because this is the most visible position. The pattern propagation factor in this area proves that.

Figures 5.15e and 5.15f show the wind turbine RCS evolution that turns form the state 0 to $\frac{\pi}{3}$ ($\alpha$ from 0 to $\frac{\pi}{3}$). Actually, this is the period of a signal evolution. Then the signal repeats itself. This is the first turbine of the Beinn Tharsuinn wind farm. With respect to the radar it has $\theta = 91^\circ$, $\varphi = 80.6^\circ$. The peak of RCS takes place when the turbine has a maximal visible surface, i.e. $\alpha = 0$, or, in other words, when one blade stands vertically. Also this result corresponds with previous publications and calculations [29, 7]. Figures 5.15e and 5.15f are based on different electromagnetic field. Thus, in order to compute RCS, presented in Figure 5.15e, we only use the amplitude of the electromagnetic field (Figure 5.15c). RCS shown in Figure 5.15f takes into account the complex field, in other words - an amplitude and a phase (Figures 5.15c and 5.15d respectively). One can see that the ordinates of the Figures 5.15c and 5.15d mean the altitude and corresponds with dimensions presented in Figure 5.14 (-67 m .. 34 m). The revolution speed in every example is 13 rpm.
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(a) Disposition of the turbine

(b) Terrain profile and PPF

(c) Amplitude

(d) Phase

(e) RCS without the phase (only an amplitude)

(f) RCS using the complex electromagnetic field (an amplitude and a phase)

Figure 5.15: Turbine 1, range 32262 m

The reason why we show the Figure 5.15e is that, before, we took into account only an amplitude because APM, initially, does not compute the phase of the field. One of the objects of this study is to retrieve the phase in order to compute RCS using a complex electromagnetic field (that is shown in Chapter 4 in details). Now we can compare the impact the previous version (Figure 5.15e) and the new one (5.15f).

An electromagnetic field depends on the place in the space. If we take the first turbine of the Beinn Tharsuinn wind farm and relocate 1500 m further, we can calculate the complex field and, more importantly, simulate RCS. So, changing the disposition of the first turbine, angles remain the same $\theta = 91^\circ$ and $\varphi = 80.6^\circ$, but the distance radar/turbine increases from 32262 m to 33762 m (+1500 m). As we can see (Figure 5.15b) the turbine is now situated behind the hill in a little hole. Let us examine the RCS there (Figure ??) and compare with the original disposition (Figure 5.15).
5.4 Recommendations as a Result

The Beinn Tharsuinn wind farm is situated on the hill at a height 510-550 m (Figure 5.2). If the wind farm is only being considered to install, we can recommend the disposition, where the farm has less influence. Despite that we simulated only one turbine, it is possible to spread its parameters to the whole wind farm. RCS of the turbine on the current disposition (Figure 5.15f) is higher than the RCS if the turbine would operate 1500 m further (dozens-hundreds times). At the same time the altitude decreases from 540 m to 450 m. Therefore, it is necessary to propose new disposition because the wind farm impact will be less. If the position of the wind turbine producer and its customer is flexible and they are ready to lose some power efficiency, than the wind farm can be built 1500 m further.

Meanwhile, the new location does not always lead to desirable result. It is necessary to have in mind a duct effect, when due to the special refractivity profile, electromagnetic waves can propagate behind the hill (Figure 5.2). That is why we need to use the propagation model like APM.
Chapter 6

Recommendations for Further Work

6.1 Pseudo 3D propagation

APM is a powerful tool used by different software such as AREPS, NEMESIS and TEMPER. All of them operate in 2D mode.

One of the most successful previous projects regarding pseudo 3D study is the research of QinetiQ, the UK [29]. However, they calculate RCS of wind turbine independently from the presence of the terrain. There are some other limitations in their work as well, which our study avoids. Using directly APM source code we can make more powerful tool met our requirements. Before some pseudo 3D studies based on PE have been provided and, recently, there were published a few articles [30, 23, 14].

Initially, APM requires a list of input parameters of the source, space and terrain, and it gives 2D image of propagation.

This module written in Matlab (see DVD) reads the DTED data and runs APM for every layer according to the lateral resolution. At the same time it uses all the set of APM parameters. The module detects the DTED level (1, 2, 3) in order to set the required resolution.

To show the results of this module, we take the Inverness airport in the UK, where Star 2000 operates in the presence of the wind farm.

In our case, we use DTED of level 1 from data E28 N45 (area N42-N60, W014-E082) 100 km X 80 km, which is in Figure 6.1a.
Basing on this terrain, the written Matlab script runs APM for every layer with the defined step. The result of this is shown in Figure 6.1b. Finally, one can combine previous images and receive pseudo 3D propagation model (Figure 6.1c).

Obviously, the pseudo 3D propagation model has similar problems as APM does:

- Backscatter waves are not considered;
- Terrain is approximated into rectangles;
- Initial theoretical assumption of used APM models.

The main shortcoming of pseudo 3D propagation model is the absence of the consideration of a horizontal propagation. In fact, this is the reason why the model is called “pseudo”.

In spite of these drawbacks, pseudo 3D propagation model could became the useful tool in wind farm problematic. To predict the influence of wind farms on the ATM radar we offer the method based on the following steps:

1. Wind farm RCS based on the complex PPF considering the real terrain. Here we need APM, its application on the 3D environment, CAD of the wind turbine and RCS software.

2. Simulation of the wind farm impact on the radar. Here we need to know the performance of our radar with its probability thresholds and the tool to simulate an output of the radar.
3. Solution to reduce the wind farm impact. Here we need the tool to automate the previous steps (written in Fortran 90 and in Matlab at least) in order to receive different scenarios and to choose the more sufficient one. ASTRAD is an excellent tool to realise this step.

Another advantage of this study is that it gives spectacular results (Figure 6.1). It could be useful for marketing aspects.

State-of-the-art of the pseudo 3D model is given in Subsection 2.4.2.

Otherwise, if the pseudo 3D model does not satisfy our needs, it is necessary to use a vector PE model. There is no successful software that can replace 2D PE. Therefore, one can wait when the vector PE model will appear on the market or develop by ST&I. However, this is a very complicated task that needs time and resources.

### 6.2 Publications & Patents

Publications and patents should be made as soon as possible. According to the patent analysis we can declare that still there is no patents that give the solution for the radar regarding wind turbines. We have been searching patents in databases of European Patent Office \(^1\), World Intellectual Property Organization \(^2\) and in Google Patents service \(^3\).

In our case, the object to be patented is not a process, machine, article of the manufacture or composition of matter. This is the method to evaluate the wind farm influence. It includes the set of software and mathematical instrument with defined algorithm. Therefore, it could be difficult to patent the method. However, in practice it is possible to receive this patent in the U.S., which is called a software patent. In other countries, especially with the developed wind power industry, one can obtain a utility model that is very similar to the patent, but usually has a shorter term (often 6 or 10 years) and less stringent patentability requirements. PCT application is very expensive (about 30000 €).

Another way to protect our intellectual property is to publish the articles. There are a lot of presentations and reports about radar and wind turbines. At the same time it is hard to find the article in famous scholarly journal. Nowadays, the publications are closely related with the patents and play the role of state-of-the-art when the patent application is considered. Thus, this is the easiest way to prevent the potential use of our ideas. In general, it is important to deal with both societies - the electronics and wind power industry.

On the part of the electrical and electronic engineering, IEEE journals and magazines are appropriate. There are a few relevant journals: Antennas & Propagation Magazine, Antennas and Propagation, Control Systems and Technology, Signal Processing, etc. Also IEEE conferences offer to publish: Radar Conference, Waveform Diversity & Digital Radar Conference, etc.

On the part of the wind power industry, the possible journals are Renewable Energy World Magazine, Wind Engineering, Wind Energy Weekly, etc.

### 6.3 Phase of APM

In Chapter 4 we show how to retrieve the phase from APM. However, there is one bug that gives a reason for concern. As one can see from Figures 5.8b and 5.8c there are horizontal “teeth”, however theoretically the phase should last smoothly and without big leaps. There are two possible solutions of that. We can shift the result of APM. It means when we have the phase, we can find all the leaps and make a smooth line shifting one after another. This solution concern only the effect.

Another solution is to find a bug in APM source code. That seems more preferable because it solves exactly the cause but not the effect.

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\(^1\)www.espacenet.com/
\(^2\)www.wipo.int/pctdb
\(^3\)www.google.com/patents
Chapter 7

Conclusion

Look, your worship, what we see there are not giants but windmills [13].

- Sancho Panza

Considering the statement of a question given in Introduction and understanding the problem, we gave an outline of possible solutions to mitigate the wind farm influence such as a signal processing, air traffic management, construction and materials of wind turbines, and how to choose the disposition of the wind farm, so that its impact will be minimal. Among proposed solutions we have stopped on the last one. So the visibility of the wind farm for the radar is determined by RCS. In order to receive RCS it is necessary to have a 3D model of a turbine and to know an electromagnetic field around the turbine that comes from the radar through the atmosphere. We showed how to draw a satisfactorily 3D model basing on specifications and on standard airfoils. The electromagnetic field can be found by propagation models. We considered different modern models and chose PE, which is implemented in APM. Afterwards we improved APM source code in order to have the complex field - with an amplitude and with a phase. Finally, we proposed to combine RCS computation, propagation model and CAD model of the turbine together using ASTRAD with connecting elements written in Matlab.

The Chapter [5] brought together ideas considered above. In order to show the practical application of proposed solution, we took an existed wind farm in Beinn Tharsuinn, the UK and the radar STAR-2000 developed in Thales Air Systems. We evaluated two possible disposition of the wind farm (1500 m between them). Finally, we received RCS of the wind turbine from these dispositions. There is a huge difference between two locations. From the first position the wind turbine reflects 30 times more energy than from the second one. It means that the farm could be almost invisible for the radar and, therefore, cause no problems for the air traffic management. We did not concern ASTRAD to automate this solution and did the algorithm “manually”. The reason is that it can be supplemented with another tools like pseudo 3D model that has been considered as a further work.

The reasonable question could be why do we apply the complicated propagation model? Why do not we use the terrain profile only? Indeed, using the terrain profile we can hide the turbine from the radar. However, the diffraction, reflection and refractivity make the propagation more complicated and not obvious. It depends on different parameters of the surface, atmosphere and weather conditions. This data is known and statistically constant. Therefore, we proposed the means for an assessment of the wind farm impact on the radar.

Also we showed the possible collaboration with different actors of the wind power industry.
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