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# EUROCONTROL Guidelines

**EUROCONTROL Guidelines  
on How to Assess the Potential Impact of  
Wind Turbines on Surveillance Sensors**



**Guidelines on How to Assess the  
Potential Impact of Wind Turbines  
on Surveillance Sensors**

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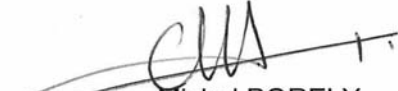


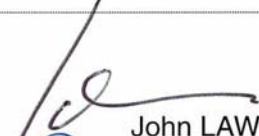



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| <b>Abstract</b>  |                                       |                              |                         |
| <p>This document provides guidelines for Air Navigation Service Providers (ANSP), and also wind energy developers, on how to assess whether or not wind turbines could impact upon the provision of surveillance services currently provided and identifies some possible means of mitigation.</p> <p>This document aims at maintaining the necessary levels of safety and efficiency of surveillance related Air Traffic Services whilst supporting to the maximum extent possible the development of wind energy.</p> <p>The proposed process defines different geographical zones, based on simple criteria, for each type of sensors (radar only for the time being). For each of these zones different conditions are defined to ensure that the impact of the wind turbine is tolerable. In the "safeguarding" zone, the closest area to the sensor, wind turbines are not allowed to be built. In the second zone, wind turbines can be built provided that a specific impact assessment analysis demonstrates that the impact can be tolerated. In the third zone, wind turbine can be built on the basis of the results of a simple and generic impact assessment analysis that is further described in this document. In the last zone, the impact is acceptable or even non-existent.</p> |                                       |                              |                         |
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| <b>Contact Person(s)</b>   |                                       | <b>Tel</b>                   | <b>Unit</b>             |
| Michel BORELY  |                                       | +32 2 72 91161               | CND CoE/CNS/SUR         |

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| AUTHORITY  | NAME AND SIGNATURE   | DATE        |
|--|--|-------------|
| Author:<br>Wind Turbine Task Force   | <br>Michel BORELY<br>Secretary of the Wind Turbine Task Force | 17/05/2010  |
| Head of SUR Unit (acting)  | <br>Jean Marc DUFLOT   | 17-05-2010  |
| Head of CNS Centre of Expertise (acting)                                     | <br>Jacky POUZET   | 19-05-2010  |
| Surveillance Programme Manager   | <br>John LAW  | 25 May 2010 |
| Head of SES Framework Development Unit                                       | <br>Peter GREEN   | 27 May 2010 |
| Deputy Director SESAR Contribution   | <br>Bernard MIAILLIER                                       | 21-05-2010  |
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EUROCONTROL Headquarters  
96 Rue de la Fusée  
B-1130 BRUSSELS

Tel: +32 (0)2 729 4715

Fax: +32 (0)2 729 5149

E-mail: [publications@eurocontrol.int](mailto:publications@eurocontrol.int)

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## EXECUTIVE SUMMARY

Many countries have set ambitious renewable energy targets for the year 2020. Meeting these targets requires a considerable deployment of renewable electricity generating capacity such as wind turbines. Wind turbines can have a detrimental impact on the functioning of Air Traffic Control (ATC) surveillance.

This document provides an approach based on an early and constructive dialogue promoting reciprocal transparency between Air Navigation Service Providers (ANSP) and wind energy developers to maintain the necessary levels of safety and efficiency of surveillance Air Traffic Services whilst supporting the development of wind energy.

The document provides three elements:

- A framework process further, supported by
- A methodology to assess whether or not wind turbine could impact on the provision of surveillance services
- A (non-exhaustive) list of possible measures to be applied to the air traffic control system or wind farm to mitigate that impact.

The proposed process includes an assessment methodology that defines different geographical zones, based on simple criteria, for each type of sensor (radar only for the time being). For each of these zones different conditions are defined to ensure that the impact of the wind turbine is manageable from an operational point of view. In summary these are as follows, in the “safeguarding” zone, the closest area to the sensor, wind turbines are very likely to cause harmful interferences. In the second zone, wind turbines could be built provided that a specific impact assessment analysis demonstrates that the impact can be managed. In the third zone, wind turbines could be built on the basis of the results of a simple and generic impact assessment analysis that is further described in this document. In the last zone, from a surveillance perspective, wind turbines could be built without any constraints.

The process also foresees wind energy developers and Air Navigation Service Providers mutually assessing possible mitigation options.

The document was written by a group of civil and military surveillance experts from the ECAC countries. The procedures described are a consolidation of practical experiences supplemented by the results of third-party studies.

It is recognised that the state of knowledge and the state of technology is continuously evolving. Therefore it is desirable to keep the document updated by modifying the approach when appropriate and adding new mitigation options when available.

**The application of the procedures outlined in this document is not mandatory.**

EUROCONTROL makes no warranty for the information contained in this document, nor does it assume any liability for its completeness or usefulness. Any decision taken on the basis of the information is at the sole responsibility of the user.

It is noted that only ATC surveillance related aspects are covered in this document. The readers are advised to ensure that all parties that may be impacted by such deployments are adequately consulted.



## 1 INTRODUCTION

### 1.1 Background

Air Navigation Service Providers (ANSP), throughout Europe, are legally responsible for the safe and expeditious movement of aircraft operating within their designated airspace. To undertake this responsibility, each has a comprehensive infrastructure of surveillance sensors (including radars), communication systems and navigational aids.

All these ground systems have an interface with the aircraft through a Radio Frequency (RF) link. Any structure that is located between a ground-based surveillance system and an aircraft has the potential to disturb the RF link between the ground system and the aircraft.

A large number of wind turbines are being deployed within the ECAC countries in order to support the strategy of increasing the share of renewable energy (e.g. 20% by 2020 for EU states).

Both communities of stakeholders have set ambitious development objectives for the next years, and it is therefore essential to ensure that each community achieves its objectives without detrimental impact on the other's.

Recommendations such as European Guidance Material on Managing Building Restricted Areas [RD 3] have been published for protecting an ANSP's Air Traffic Management infrastructure against static structures like buildings, telecommunication masts, etc. However wind turbines are not static structures (blades are turning, blade orientation is changing, nacelle is rotating), the recommendations defined for static structures are not applicable to wind turbines.

In responses to concerns regarding interference between surveillance sensors and wind turbines, the EUROCONTROL Surveillance Team established, at the end of 2005, a Wind Turbine Task Force and gave it the responsibility to develop a recommended methodology that could be used to assess the potential impact of structures such as wind turbines on Surveillance Systems and to provide suggestions for possible mitigation options.

This methodology and the framework process, in which it is embedded, are described in this document. They aim at maintaining the necessary levels of safety and efficiency of surveillance related Air Traffic Services whilst supporting to the maximum extent possible the installation of wind turbines.

### 1.2 EUROCONTROL Guidelines

EUROCONTROL guidelines, as defined in EUROCONTROL Regulatory and Advisory Framework (ERAF) [RD 5], are advisory materials and contain:

*“Any information or provisions for physical characteristic, configuration, material, performance, personnel or procedure, the use of which is recognised as contributing to the establishment and operation of safe and efficient systems and services related to ATM in the EUROCONTROL Member States.”*

Therefore, the application of EUROCONTROL guidelines document is not mandatory.

In addition, it is stated in [RD 6] that:

*“EUROCONTROL Guidelines may be used, inter alia, to support implementation and operation of ATM systems and services, and to:*

- *complement EUROCONTROL Rules and Specifications;*
- *complement ICAO Recommended Practices and Procedures;*
- *complement EC legislation;*
- *indicate harmonisation targets for ATM Procedures;*
- *encourage the application of best practice;*
- *provide detailed procedural information.”*

### **1.3 Objective of this document**

The objective of this document is to provide a concise and transparent reference guide for both ANSPs and Wind Energy developers when assessing the impact of wind turbines on ATC surveillance systems.

This reference guide relies on a framework process including an assessment methodology and mitigation options. The assessment methodology is based on establishing when ATC services based on surveillance information could be affected beyond manageable level by the construction of a proposed wind turbine development.

For radar, the key performance characteristics are defined in the EUROCONTROL Standard Document for Radar Surveillance in En-route Airspace and Major Terminal Areas [RD 1]. They are used throughout this document when assessing radar performance.

For the time being the assessment methodology is limited to mono-static ATC radar surveillance sensor (Primary Surveillance Radar – PSR, Secondary Surveillance Radar – SSR); it is the intention to extend it to other technologies like Wide Area Multilateration (WAM), Automatic Dependent Surveillance Broadcast (ADS-B) and Multi-Static Primary Surveillance Radar (MSPSR) if relevant.

Initial studies showed that these technologies, which currently have different levels of maturity<sup>1</sup>, are likely to be less susceptible to wind turbines than radars. Therefore, they could be implemented as possible mitigations in certain cases, provided that their deployment has been fully validated in the ATC context. Other currently available mitigations are described in section 4.6.

Wind turbines can also have detrimental impacts upon other aspects of air transport. Such aspects include, but are not limited to, performance reduction of ATM infrastructure (Communication, Navigation), constraints on procedure design, airspace planning and design, minimum safe altitudes, climb rates of aircraft, descent rates of aircraft, procedures to ensure that wind turbine locations are correctly represented on maps and in terrain avoidance tools, procedures to ensure that they are appropriately lit etc.

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<sup>1</sup> *It should be noted that MSPSR maturity is currently at a research status.*



These aspects have to be addressed in accordance with the relevant documents. In particular, the European guidance material on managing Building Restricted Areas (BRA) (ICAO doc 015 [RD 3]) provides some specific recommendations in its Appendix 4 regarding wind turbine assessment for navigation facilities.

The relationships between these guidelines and ICAO doc 015 [RD 3] are further described in section 1.9 below.

## **1.4 Designing the Assessment Methodology**

When producing this methodology the objective was to document a mechanism that was simple in its application and transparent in its structure.

Secondary Surveillance Radars (SSRs) are classified as a cooperative surveillance technique – equipment on board the aircraft receives an interrogation from the ground station and cooperates by replying with a signal broadcast of its own. The need to interface with the transponder carried by the aircraft means that, whilst various technologies can be employed (classical sliding window SSR, Monopulse SSR and Mode S SSR), Secondary Surveillance Radars are well standardised. This high degree of consistency between co-operative surveillance systems allows the prediction of a single range beyond which it is believed that wind turbines would have only a manageable impact upon the performance of an SSR system. Up to that range the deployment of wind turbines would only be permitted if a comprehensive study demonstrates that no detrimental impact will arise.

Primary Surveillance Radars differ in that the aircraft is non-cooperative and the only 'interface' is the electro-magnetic energy reflected from the body of the aircraft. In this sense the technique is classified as non-cooperative. The disparate nature of non-cooperative surveillance systems, such as Primary Surveillance Radar (PSR), requires a more complex approach tailored to the specific technology employed and the environment in which it is operated.

Whilst the basic physics behind non-cooperative target detection are common it can be said that no two designs of Primary Surveillance Radars achieve the same end goal by following the same approach. The following, non exhaustive, list highlights some of the considerations that should be taken into account to carry out a full, detailed and analytical assessment into whether a technical interference would result from the placement of a wind turbine in the proximity of a PSR:

- Antenna Design – ATC PSR systems normally use an antenna with a complex Cossec2 beam pattern, typically with two beams (one Tx/Rx and one Rx only) – each beam with a different pre-set elevation angle. Each antenna has different characteristics, from the electrical elevation, through to gain and Integrated Cancellation Ratio and such parameters impact upon how much of a wind farm would be 'illuminated' by the radar and how much of the return would be passed to the subsequent receiver stage. The horn arrangement may support linear or circular polarized transmission or be switchable between the two. Phased array antennas present a different approach.
- The turning gear rotating the antenna is not an immediate consideration except for the fact that many can apply mechanical tilts to the antenna pattern to optimise either low level detection or minimise ground clutter returns.

- The receiver stages of the PSR would normally permit the application of one or more Sensitivity Time Control (STC) laws to reduce the impact of ground clutter. The STC is normally integrated with multiple beam switch points (switching between the signals received from either the high or low antenna beam).
- The transmitted signal can differ significantly depending upon the technology employed – either a magnetron, a solid state system or a travelling wave tube etc. The choice of driver influences the waveform, the number and characteristics of the pulses, the frequency band, the utilisation of frequency diversity schemes etc. The frequency band selected can also impact upon the susceptibility of the system to anomalous propagation effects.
- The signal processing techniques and capabilities differ – sub-clutter visibility and ground clutter rejection capabilities vary and the rejection capabilities differ significantly between different types of sensor, types of signal processing, such as MTI or Moving Target Detection (MTD) and the system parameter settings established during site optimization and flight trials.
- Plot extraction techniques are often employed to facilitate further processing and to reduce the bandwidth of the data signal to be transmitted from a remote PSR to an ATC control centre. The resulting data reduction also removes the possibility of an ATC to review the ‘raw video’ of the radar and this can impact upon the ability of a controller to monitor flights over areas where wind farms are deployed.
- Some PSRs are equipped with mono-radar track processing capabilities and these could be used to suppress radar returns from over wind farms. Unfortunately this can also often result in suppressing the returns from valid targets as well – the performance of any mono-radar tracker will therefore also need to be taken into account when conducting an assessment of whether wind farms will impact upon the performance of such systems.
- The geographic environment plays a great part in defining radar coverage. Considerations such as radar horizon would obviously drive requirements for tower heights. Proximity to the sea or large areas of flat or marshy land can result in beam ducting whilst the shape of mountains and whether they are sparsely or heavily covered in either snow or vegetation can also increase or decrease the radar returns. The nature of the aircraft to be detected and the airspace in which they fly will also determine design and deployment considerations.

The authors of the document have taken key characteristics into account to produce a simplified approach to be used when conducting an initial assessment of whether wind turbines deployed in the proximity of a PSR would result in performance degradation for the latter.

Whilst this initial assessment may err on the side of caution from the radar operators perspective, the authors also fully support the wind farm applicant in their right to conduct their own detailed assessment and to this end have provided some guidelines for how to perform such an assessment – these guidelines can be found in the supporting annex of this document.

Surveillance providers will be able to assist in the detailed assessment by providing key radar characteristics to be used in the detailed assessment performed by the applicant but, depending upon the PSR, additional support may also need to be sought from the manufacturer of the system.

To summarise, the approach adopted within the methodology is for an initial safeguarding region in the vicinity immediately surrounding the surveillance sensor within which all planning applications would be objected. Beyond this restrictive zone lie regions where progressively reducing levels of proof are required. The approach is common for both the cooperative and non-cooperative surveillance techniques covered within this document.

## **1.5 Application of the assessment methodology**

The methodology is based upon the following zone arrangements:

- **Zone 1: Safeguarding Zone (PSR and SSR):**  
An initial restrictive or safeguarding region that surrounds the surveillance sensor. No developments shall be agreed to within this area.
- **Zone 2: Detailed Assessment Zone (PSR and SSR):**  
Following the safeguarded region is an area where surveillance data providers would oppose planning applications unless they were supported by a detailed technical and operational assessment provided by the applicant and the results of which are found to be acceptable to the surveillance provider.  
The detailed technical assessment shall be based upon the approach detailed in paragraph 4.4.
- **Zone 3: Simple Assessment Zone (PSR only):**  
Beyond the detailed assessment zone is a region within which a simple assessment of PSR performance, as detailed in section 4.3, should be sufficient to enable the surveillance data provider to assess the application.
- **Zone 4: Accepted Zone (PSR and SSR):**  
Beyond the simple assessment zone are areas within which no assessments are required and within which Surveillance Service providers would not raise objections to wind farms on the basis of an impact to surveillance services.

It is important to note that the zones are based upon a combination of range from the sensor and radar line of sight and therefore are not necessarily annular bands.

If necessary ANSPs and wind energy developers should discuss and agree mitigation options (see paragraphs 2.6 and 4.6) to overcome issues that have been identified in the course of the assessment.

## 1.6 Structure of the document

This document is structured in 5 chapters and 5 annexes:

- Chapter 1, this chapter provides an introduction to the document describing its background, its objective, its approach, its structure and its use.
- Chapter 2 describes the process flow when assessing the impact of wind turbines on surveillance sensors.
- Chapter 3 defines the required input information needed to undertake the previously defined process.
- Chapter 4 specifies for radar sensors the different zones, the simple impact assessment process, and the issues to be addressed, as a minimum, in the frame of the detailed assessment process. It also contains a table identifying possible mitigation options.
- Chapter 5 provides the lists of referenced documents and the definition of acronyms.
- Annexes A to C justify and describe the different equations that are used in the different assessments described in chapter 4.
- Annex D provides the justification for the selection of the zone 2 range defined for SSR.
- Annex E proposes a wind energy project description pro-forma.

## 1.7 Use of this document

This document is intended to be read and used by:

- Civil and military Air Navigation Service Provider (ANSP)
- Surveillance data provider
- National Supervisory Authority (NSA)
- Civil and military aviation authority
- Wind energy developer

EUROCONTROL makes no warranty for the information contained in this document, nor does it assume any liability for its completeness or usefulness. Any decision taken on the basis of the information is at the sole responsibility of the user.

## 1.8 Conventions

The following drafting conventions are used in this document:

- **“Shall”** – indicates a statement of specification, the compliance with which is mandatory to achieve the implementation of these EUROCONTROL Guidelines.
- **“Should”** – indicates a recommendation or best practice, which may or may not be applied.
- **“May”** – indicates an optional element.

## **1.9 Relationship with ICAO Doc 015 [RD 3]**

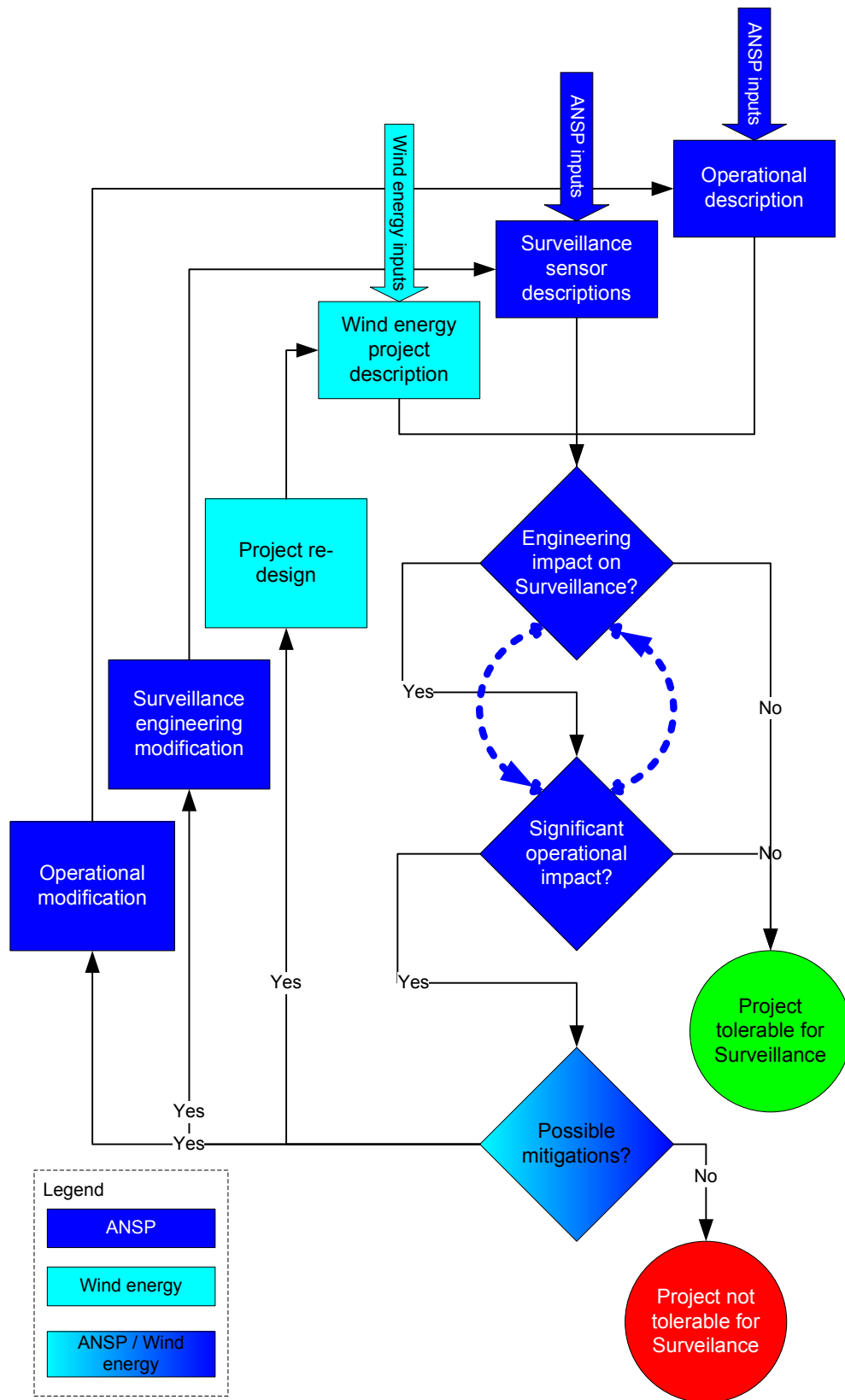
The aim of this document is to supplement ICAO doc 015 [RD 3]. In particular with respect to § 6.4 where it is stated that: “*For surveillance and communication facilities it is recommended that wind turbine(s) should be assessed at all times even outside the BRA for omnidirectional facilities.*”

## 2 IMPACT ASSESSMENT PROCESS

Figure 1 describes the generic process to be followed by ANSP and the wind energy developers when assessing the impact of a wind turbine project on surveillance infrastructure. This diagram has deliberately been kept at a high level to be compatible with formal and informal requests.

Wind energy developers are invited to initiate this process on the basis of these guidelines as soon as possible in the preparation phase of their project. At the earliest stages of the project, when there is more room for adaptation, it is anticipated that cost effective mitigation options (see section 4.6 for some possible mitigations) could be agreed; whereas at later stages, viable mitigation options could be more difficult to define and to agree on.

In order to facilitate this dialogue, it is recommended that ATM stakeholders (e.g. ANSP, NSA) publish a single point of contact (e.g. a generic email address) through whom initial contact can be established.



**Figure 1: Impact Assessment Process**

On Figure 1 the activities have been allocated on the basis of a formal request. In theory any activity can be undertaken by anybody provided that they have all the required pieces of information and the relevant knowledge.

## **2.1 Wind energy project description**

This is a wind energy developer activity; it consists of collecting all the relevant wind energy project information to perform an impact assessment on the proposed development.

The information to be provided is described further in Section 3.1.

This project description shall be provided with any formal request to get a formal advice from the ANSP. It is to be noted that this process only addresses the impact on surveillance infrastructure, whereas the project may have other impacts that the ANSP have to assess. It is also to be noted that formal requests will be governed by state policy and as such will have to respect a number of national rules.

This project description may also be provided through an informal request at the earliest possible stage to avoid any further nugatory works. This is typically an informal approach to gauge reaction to a new development which is still at the exploratory stage of design. This should be encouraged, as early changes to a development proposal, prior to formal submittal to the planning authorities, are much easier to introduce to meet the needs of the ANSP.

By whatever route notification is received, it is important that as much of the relevant information is included as possible. At a pre-planning stage precise details of turbine locations and dimensions are often not fixed therefore any results based on this incomplete information must obviously be caveated such that relevant decision making authorities treat them with caution. Any change in the design proposal will require a re-assessment.

## **2.2 Surveillance sensor description**

This is an ANSP activity; it consists of collecting all the relevant surveillance sensor information to perform an impact assessment on the proposed development.

In case the sensor is associated to a Far-Field Monitor (FFM), information related to that FFM is also needed.

The information to be provided is described further in Section 3.2.

This surveillance sensor description shall, subject to appropriate security and confidentiality considerations, be made available on request for preliminary analysis or site selection to wind energy developer.

## **2.3 Operational description**

This is an ANSP activity; it consists of collecting all the relevant operational information (e.g. aeronautical navigation routes) to perform an impact assessment on the proposed development.

The information to be provided is described further in Section 3.3.



This operational description may, subject to appropriate security and confidentiality considerations, be made available on request for preliminary analysis or site selection to wind energy developer.

This operational description shall, subject to appropriate security and confidentiality considerations, be made available in response to a formal request attributable to a specific planning application

## **2.4 Engineering impact on surveillance**

This is an ANSP activity, which consists of assessing the potential performance impacts that the submitted wind energy project could have on individual surveillance sensors operated by the ANSP, to derive the impact it may create at the output of the surveillance system and to consider possible mitigation mechanisms that could be introduced.

The assessment is described further for each type of radar in Chapter 4.

Although it is recognised that in most cases the sensor outputs will not be provided directly to the Air Traffic Controllers, but will go through further processing stages like Surveillance Data Processing systems; there are still some cases where the sensor output is used operationally (in normal or in fall-back mode). Therefore the maximum effort should be undertaken to minimise the impact of wind turbines at the earliest stages of the surveillance chain i.e. at the surveillance sensor level.

The application of specific features at surveillance data processing level is considered as a possible mitigation. Further mitigation possibilities may also be considered – a range of these are identified in section 4.6.

At this stage, the methodology encourages an ANSP engineering department to initiate discussions with the operational staff (as shown with the curved arrows on Figure 1) to assess the potential technical and operational impacts of the wind energy project in order to identify realistic mitigation measures that, in general, have both engineering and operational implementation aspects.

## **2.5 Operational impact on surveillance**

This is an ANSP activity, which consists of assessing the impacts that the submitted wind energy project could have on the ANSP operations based on surveillance services and/or on the surveillance data service the ANSP is providing to other users.

This activity is described further for each type of radar in Chapter 4.

It is to be remembered that an ANSP is held legally accountable for the safe provision of service at all times.

As stated in paragraph 2.4 above and although the engineering and operational impact assessment stages are shown as two different boxes on Figure 1, a strong cooperation between the operational and engineering departments of the ANSP is needed to ensure that all aspects have been analysed and that all possible mitigations have been identified.

## **2.6 Possible mitigations**

This is a combined ANSP/wind energy developer activity, which consists of identifying potential modifications to the surveillance system **and/or** the operational environment **and/or** the wind energy project that could mitigate to a tolerable level the impact of the wind energy development project.

This activity should be based on a transparent, coordinated and balanced approach with the objective of finding a solution that can be agreed by all parties.

When assessing mitigation options the following criteria shall be taken into account:

- Air traffic safety is maintained
- Cost efficiency based on through life cost over an agreed time period

The detailed assessment required to judge the suitability of such mitigations is beyond the scope of these guidelines due to their site specific nature.

## **2.7 Project re-design**

This is a wind energy developer activity, which consists of taking into account in his project the possible mitigations identified at the previous stage to make the project impacts tolerable.

## **2.8 Surveillance engineering modification**

This is an ANSP activity, which consists of taking into account the possible mitigations identified at the previous stage and that are applicable to the surveillance system to make the project impacts tolerable.

It is desirable that any surveillance engineering modification should be carbon neutral and have no detrimental impact on the environment.

## **2.9 Operational modification**

This is an ANSP activity, which consists of taking into account the possible mitigations proposed at the previous stage and that are applicable to the operational environment to make the project impacts tolerable.

It is desirable that any operational modification should be carbon neutral and have no detrimental impact on the environment (e.g. noise, longer routes, etc.).

### 3 INPUT INFORMATION

#### 3.1 Wind energy project description

A simple way that an ANSP can ensure that planning authorities and developers understand what information is required prior to an assessment is by making available a pro forma which developers can complete and submit. The following list of requested information has been constructed based on the pro-forma used by different stakeholders and is further developed in Annex - E where a practical pro-forma can be found. The different parts of a wind turbine are identified on Figure 2 below.

The following parameters are needed to perform the simple engineering assessment:

- Hub height (above ground level in m)
- Rotor diameter (m)
- Turbine locations (National Grid system and/or WGS84 including terrain height)

Additional parameters could be needed to perform the detailed engineering assessment, for example:

- Wind turbine model and manufacturer
- Number of blades
- Rotation speed (Rpm) nominal and maximum
- Tower design (tubular/lattice)
- Tower base diameter (m)
- Tower top diameter (m)
- Nacelle Dimensions (width x length x height in m)
- Rotor blade material including lightening conductor

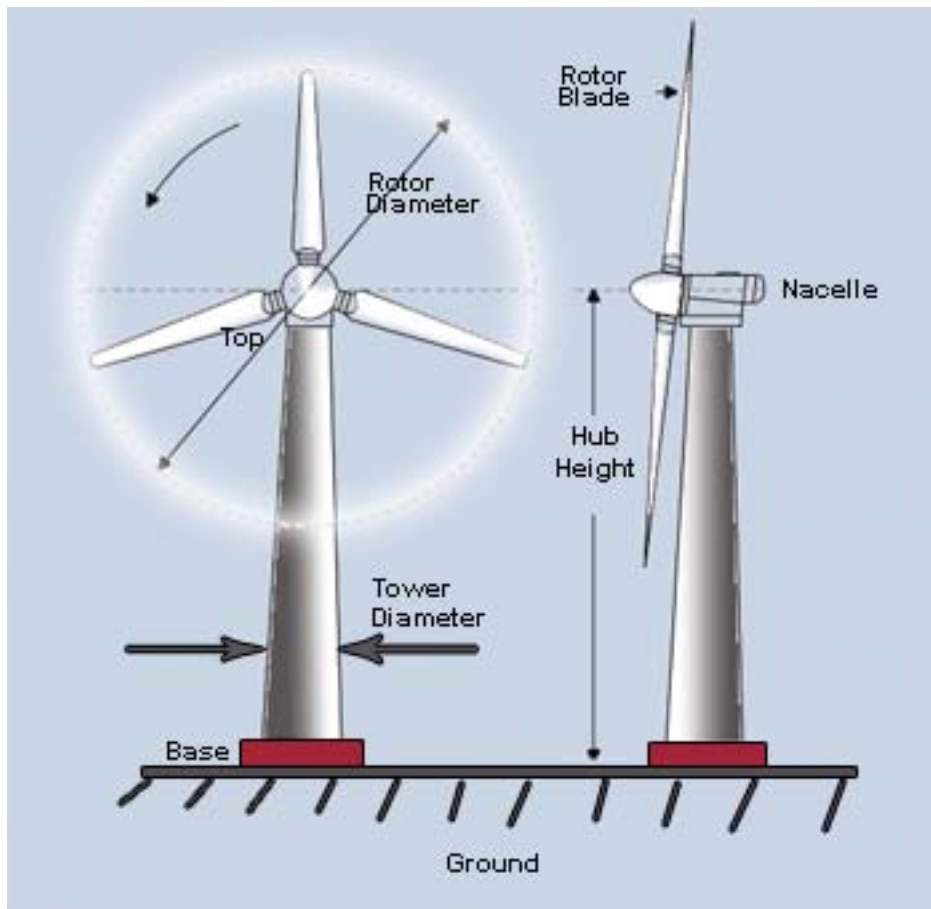


Illustration identifying wind turbine components and key parameters

**Figure 2: Wind turbine diagram**

### 3.2 Surveillance sensor description

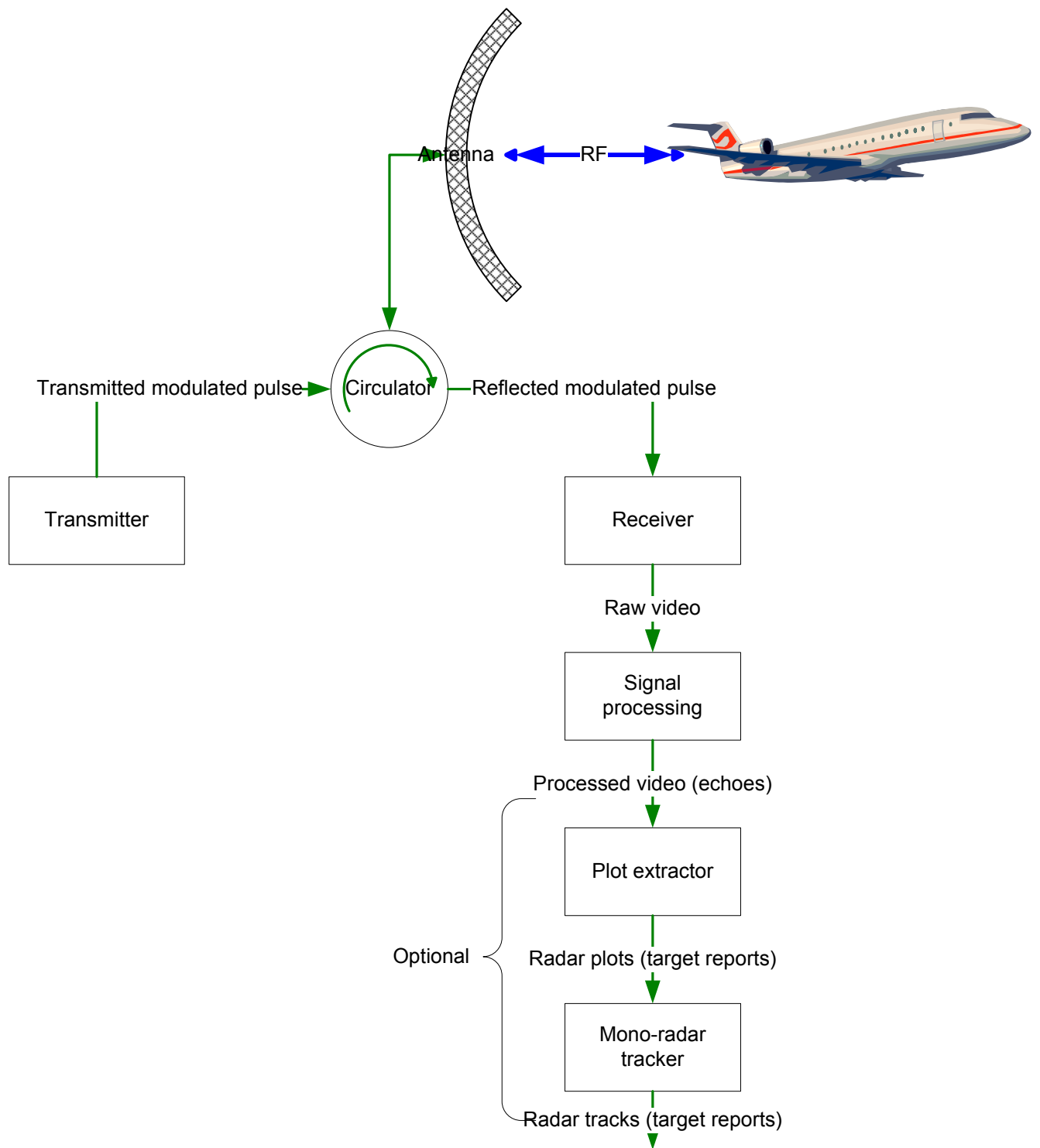
The list of information needed to undertake the simple engineering assessment is the following:

- Radar line of sight calculation method/tool
- Primary Surveillance Radar:
  - Antenna 3D position (WGS84 and/or national grid system and height above terrain)
  - Frequency range (in GHz)
  - Instrumented range (in NM)
  - Antenna horizontal beam-width at 3 dB (in °).
  - Information related to CFAR processing as required to undertake the assessment described in section 4.3.1
  - Radar processing capacities (e.g. plots, tracks)
  - Overload prevention technique

- SSR:
  - Antenna 3D position (WGS84 and/or national grid system and height above terrain).
  - Antenna horizontal beam-width at 3 dB (in °) – 2.4° by default.
- SSR/PSR far-field monitor:
  - Position (WGS84 and/or national grid system)

In addition, further parameters could be needed to perform the detailed assessment, for example:

- Primary Surveillance Radar:
  - Antenna transmit vertical pattern.
  - Antenna receive vertical pattern.
  - Antenna tilt (in °).
  - Frequencies used (in GHz).
  - Anti-reflection processing capabilities (number of reflectors, number of reflections).
  - Transmitted power (in dBW).
  - Receiver, signal and data processing capabilities.
- SSR:
  - Type: classical sliding window, monopulse, Mode S.
  - Anti-reflection processing capabilities (number of reflectors, number of reflections).
  - Receiver, signal and data processing capabilities.
  - Overload prevention technique.



**Figure 3: Primary Surveillance Radar diagram**

The diagram above illustrates the main components of a modern primary surveillance radar system; the radar output may also be at processed video or at plot level. The radar output may be connected directly to a Controller Working Position or to a multi-sensor tracker for further processing.

The picture below (Figure 4) shows a primary radar antenna co-mounted with a secondary radar antenna (on top).



**Figure 4: Primary and secondary co-mounted radar antennas**

### **3.3 Operational description**

The information needed to undertake the operational impact assessment is the 3D airspace volume, per ATC service<sup>2</sup> (e.g. 3 NM horizontal separation, parallel runway monitoring, vectoring), where surveillance information is required to support ATC operations.

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<sup>2</sup> *The different ATC services are described in Chapter 8 of [RD 4].*

## **4 RADAR IMPACT ASSESSMENT**

Information on how such an assessment can be performed is contained within the following paragraphs. The assessment shall be conducted for each sensor that has at least one wind turbine within its range coverage.

### **4.1 Radar line of sight assessment**

The first assessment that shall take place is to determine whether or not any part of the turbine will be within the line of sight of the radar (i.e. from the electrical centre of the radar antenna). If the turbines are located in a way that does not affect the surveillance sensor performance (e.g. the turbines are fully 'hidden' from the sensors by terrain or the turbines are located further away than the radar instrumented range), then consent for the development can be approved. However if a part of the wind turbine (e.g. a blade) can be in radar line of sight then there is potential for an impact upon the radar.

Tools are available to undertake this assessment. Each of them has some specific features and some limitations. The focus is put on the agreement to be reached between the ANSP and the wind energy developer to select a tool that is familiar to the ANSP and which is parameterised in accordance with the local conditions and/or the type of assessment (e.g. the accuracy of the digital terrain modelling may depend on the distance between the wind turbine and the radar and/or whether a simple or a detailed assessment is being conducted).

### **4.2 Top-level engineering assessment**

In order to facilitate this process, different zones have been defined corresponding to different levels of engineering assessment. They are summarised in the tables below.

It should be noted that Zone 2 is not a No-Go area but indicates where further consideration needs to be applied compared to Zone 3. In any case wind turbines could be placed in zone 2 or zone 3 if no intolerable impact would result from their deployment.



#### 4.2.1 Primary Surveillance Radar

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

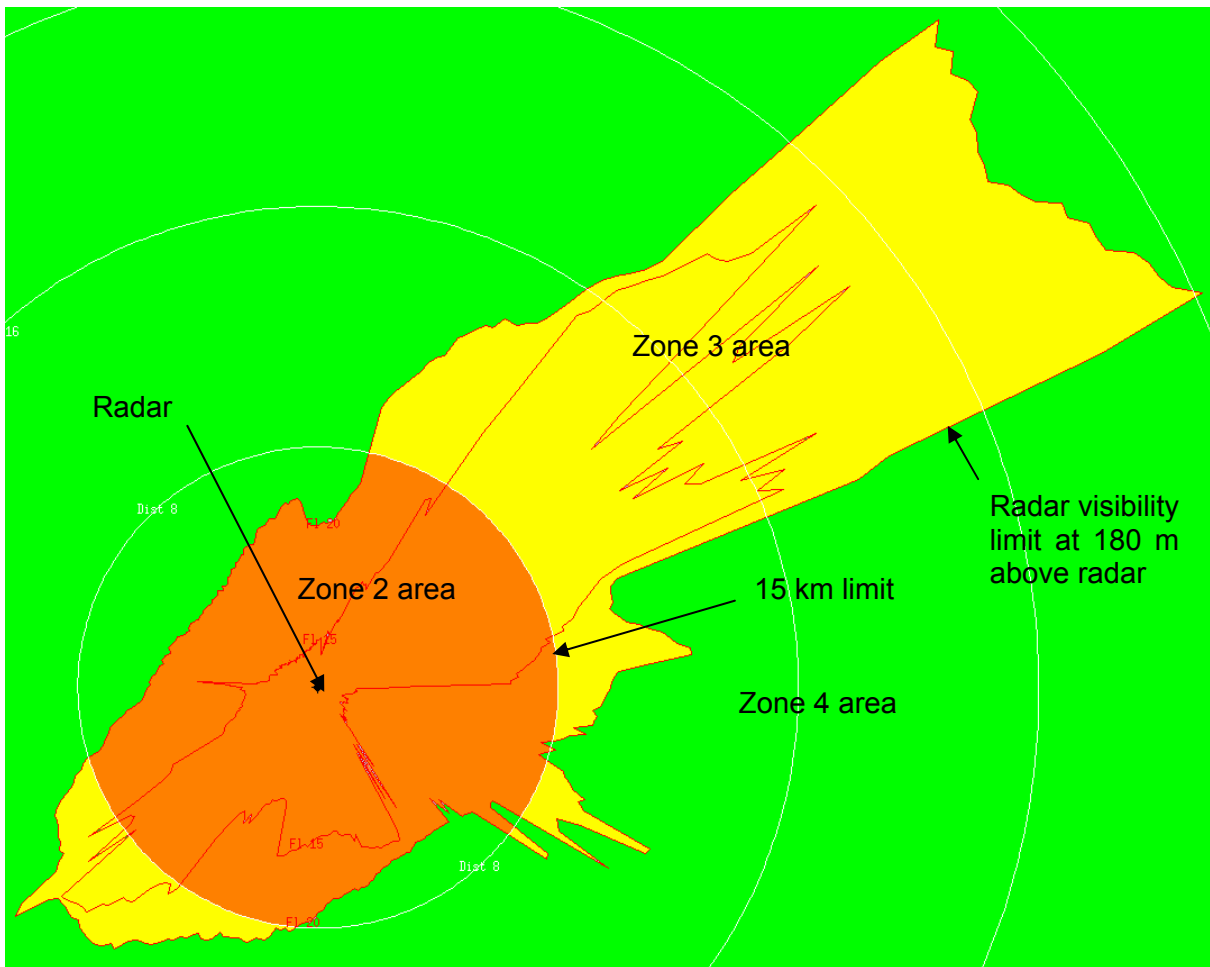
**Table 1: PSR recommended ranges**

The PSR safeguarding range where no wind turbine shall be built is derived from the recommendations provided in the ICAO EUR 015 document [RD 3] which is applicable for any obstacle ( $r$ : radius of the first cylinder on figures 2.1 and 2.2).

PSR radar designs vary considerably and the design choices made by PSR manufacturers influence the susceptibility of their radars to wind turbines (see paragraph 1.4 above). The figure for the PSR recommended limit between detailed and simple assessment is therefore derived from the best practices collected from the ECAC member states and it is also a figure recognised in the ICAO EUR 015 document [RD 3] ( $R$ : radius of the second cylinder on figures 2.1 and 2.2).

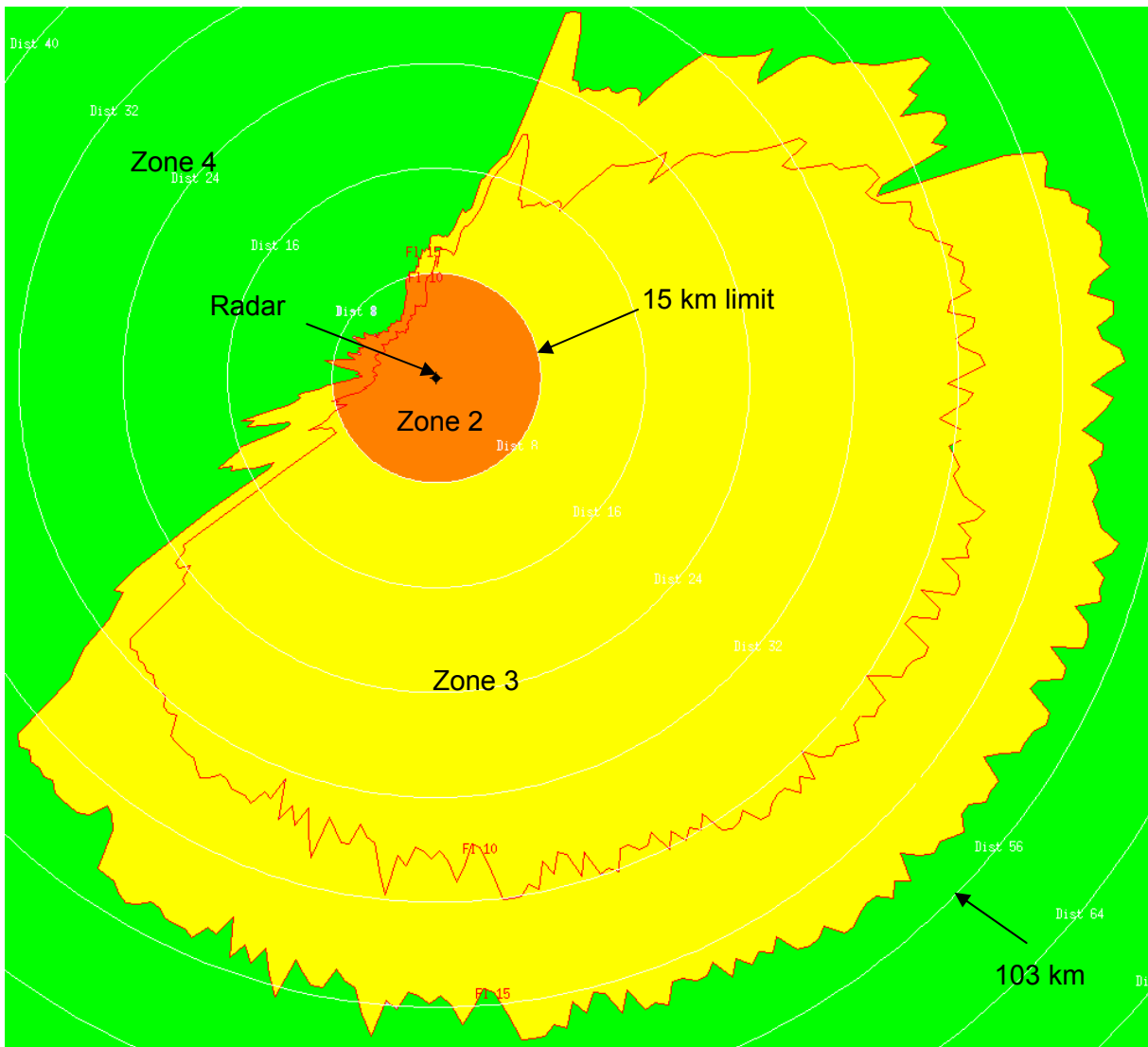
Therefore these figures are applicable to current wind turbine design, e.g. 3-blades, 30-200 m height, horizontal rotation axis. For other types of turbines, it is recommended to undertake the detailed assessment as long as the wind turbine is in radar line of sight.

When outside the radar line of sight of a PSR, the impact of the wind turbine (3-blades, 30-200 m height, and horizontal rotation axis) is considered to be tolerable.



**Figure 5: Example of zones at 180 m above a real radar**

Figure 5 above shows that the different zones are not annular bands (unless in a theoretical no obstacle environment) and their shape depends on the terrain surrounding the radar. These zones have been calculated on the basis of a real radar and, for this example, at 180 m above the radar ground level.



**Figure 6: Example of zones at 320 m above a real radar**

Figure 6 above shows another example of the different zones around a real radar at 320 m above the ground level at the radar site.

#### 4.2.2 Secondary Surveillance Radar (classical, monopulse and Mode S)

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

**Table 2: SSR recommended ranges**

The SSR safeguarding range where no wind turbine shall be built is derived from the recommendations provided in the ICAO EUR 015 document [RD 3] which is applicable for any obstacle ( $r$ : radius of the first cylinder on figures 2.1 and 2.2).

The figure for the recommended limit of SSR detailed assessment is further justified in Annex - D based on the SSR specifications provided in ICAO Annex 10 Volume IV [RD 2].

As the justifications developed in Annex - D are based on current wind turbine design, e.g. 3-blades, 30-200 m height, horizontal rotation axis. For other types of turbines, it is recommended to undertake the detailed assessment as long as the wind turbine is in radar line of sight.

It is to be noted that in the case of SSR there is no simple assessment zone.

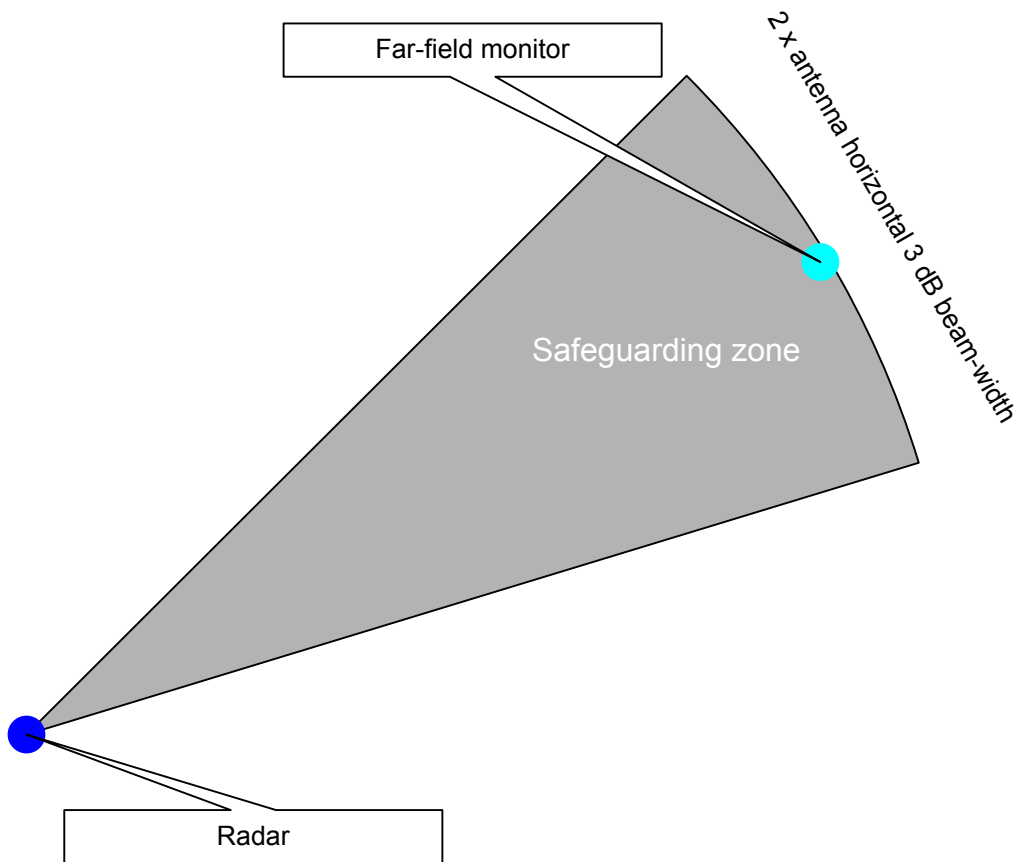
When outside the radar line of sight of an SSR the impact of the wind turbine is considered to be tolerable.

When further than 16 km from an SSR the impact of a wind turbine (3-blades, 30-200 m height, and horizontal rotation axis) is considered to be tolerable.

#### 4.2.3 Radar Far-Field Monitors (FFM)

In addition, irrespective of the zone in which the wind turbine falls, it is recommended to protect the radar far-field monitor as described below.

Wind turbines shall not be built in a sector of 2 times the radar antenna horizontal beam-width at 3dB, centred on the far-field monitor azimuth and limited up to the range of the far-field monitor (as illustrated on Figure 7 below). This is applicable to far-field monitors of primary or secondary surveillance radar.



**Figure 7: Recommended protection zone for far-field monitor**

Possible mitigations are to move either the wind turbine or the far-field monitor.

#### **4.2.4 Radar data sharing**

In case the surveillance data provided by the impacted radar is shared, the radar data user should be informed of the wind turbine project. If applicable, the engineering assessment process shall take into account any radar data quality requirements imposed by the SLA (Service Level Agreement) associated to this radar data sharing.

#### **4.2.5 Cumulative impact**

As further detailed in the following sections, the impact of wind turbines on the operational service provided by a radar depends on the number of wind turbines located in the radar line of sight. Therefore it is strongly recommended that ANSP's keep an accurate tracking of all the approved wind energy projects. With this information they will be able to conduct the impact assessment of the new project in conjunction with the neighbouring approved projects that may already affect the performance of radars.

## 4.3 Simple engineering assessment for PSR

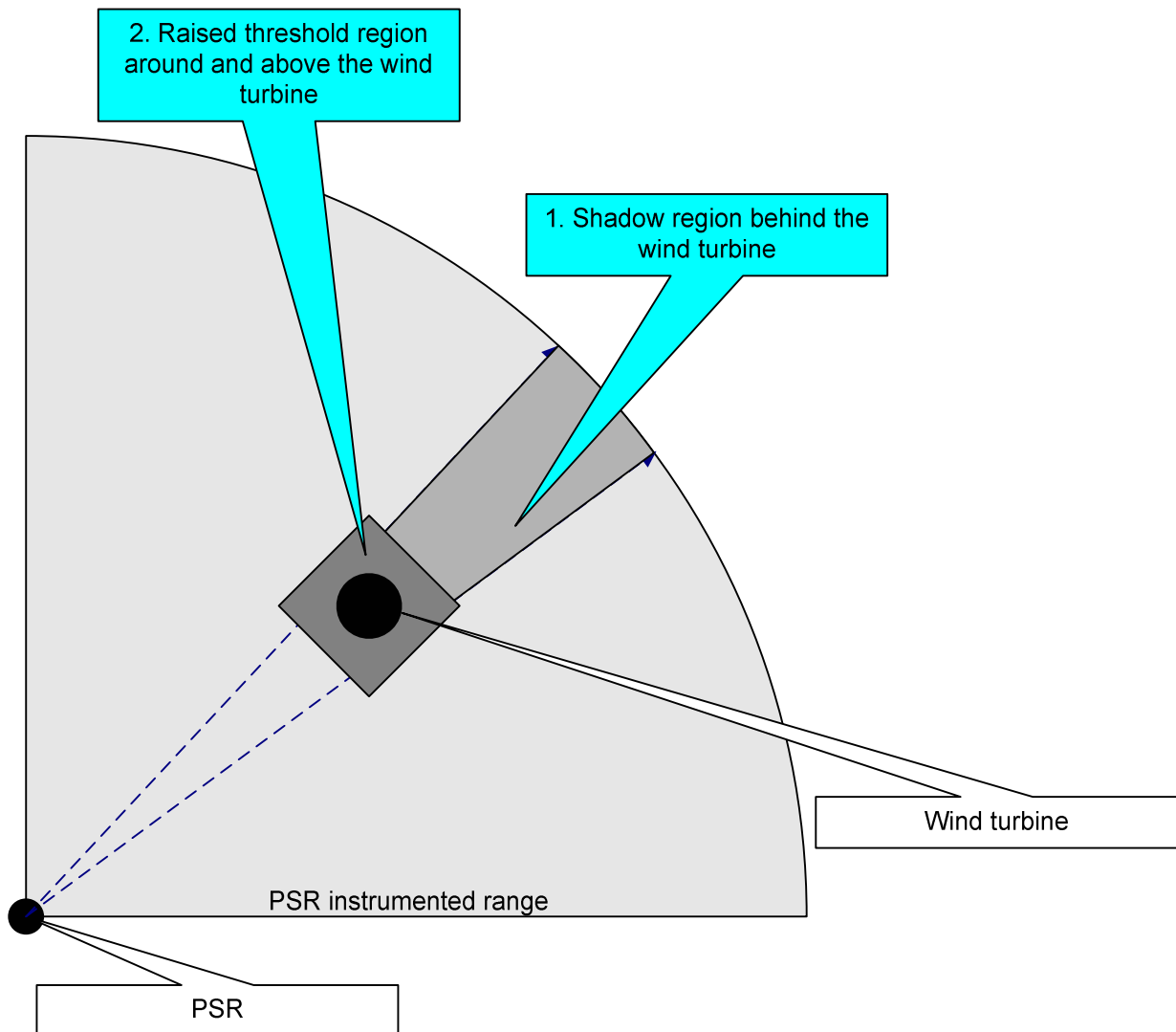
### 4.3.1 PSR Probability of detection

One of the key performance characteristic of a Primary Surveillance Radar, as defined in § 6.2.2.2 of the EUROCONTROL Standard Document for Radar Surveillance in En-route Airspace and Major Terminal Areas [RD 1], is the probability of detection.

When a wind turbine lies in the line of sight of the PSR, the probability of detection can be reduced in two ways:

- In a shadow region directly behind the turbine (region 1 on Figure 8).
- In a volume located above and around the wind turbine (region 2 on Figure 8).

The first effect is caused by the attenuation due to the wind turbine being an obstacle for the electromagnetic field. The second effect is caused by the large amount of energy reflected back by the wind turbine, causing an increase in the radar's detection threshold (CFAR) in the range-azimuth cell where the wind turbine is located and also in some adjacent cells.



**Figure 8: Shadow region behind a wind turbine and raised threshold region around and above a wind turbine**

A simple way to estimate the 2 regions indicated on Figure 8 is as follows:

1. Dimensions of the shadow region (1) can be determined using Equation 4 in annex A - 3 to calculate its width and Equation 1 annex A - 2 to determine its height.
2. The region (2) located directly above the wind turbine<sup>3</sup> is typically one to sixteen<sup>4</sup> clutter cells large, depending on the exact CFAR algorithm.

These calculations have to be repeated for each wind turbine of a wind farm and the global impact is the sum of the individual impacts. This may be achieved by overlaying the shadow zones from individual wind turbines to give an overall shadow representation.

<sup>3</sup> The effect has been observed for wind turbines at any range from the radar. Placing the wind turbines further away from the radar is therefore not necessarily a solution to this problem.

<sup>4</sup> The column of airspace can extend out from the turbine position if smearing algorithms are used in clutter map generation.

#### **4.3.2 PSR false target reports (due to echoes from wind turbines)**

One of the key performance characteristic of a Primary Surveillance Radar, as defined in § 6.2.2.3 of the EUROCONTROL Standard Document for Radar Surveillance in En-route Airspace and Major Terminal Areas [RD 1], is the number of false target reports.

Due to their large radar cross section and moving parts turbines can be directly detected by a PSR and may generate false target reports.

If the highest point of the wind turbine (hub height + half the rotor diameter) is within the radar line-of-sight, it is assumed that the turbine will be detected by the PSR. This may manifest itself in the raw/processed video that may be presented to an ATCO, in plot reports, additionally they may be promoted to a mono or multi-sensor track due to their strength or when multiple plot reports correlate to form a track.

Further radar processing techniques (see Annex B - 2) may provide protection against the generation of target reports corresponding to wind turbines.

These calculations have to be repeated for each wind turbine of a wind farm and the global impact is the sum of the individual impacts.

#### **4.3.3 PSR processing overload**

When PSR is including a plot extractor and/or a mono-radar tracker there will be a limitation in the number of inputs that it can process. If the number of PSR echoes, including those due to wind turbines, is too high, the plot processor may need to apply anti-overload techniques. Similarly, if the number of plots, including false plots due to wind turbines, is too high, the tracker may need to apply overload prevention techniques. Both may have an operational impact (e.g. reducing the operational capability of the radar).

It is to be noted that in this case the affected areas do not depend on where the wind turbines are located but on the internal design of the system (i.e. the applied overload prevention techniques).

It is assumed that the next stages of the surveillance chain (e.g. communication network and multi-sensor tracker) are compatible with the maximum PSR output capacity.



## **4.4 Detailed engineering assessment for PSR and SSR**

### **4.4.1 Generalities**

When a wind turbine is located close to a radar (less than 15 km for a PSR, less than 16 km for an SSR) a detailed impact assessment shall be undertaken unless the potential impact of the wind turbine does not cause an operational issue (e.g. if the wind turbine is not located under an ANSP operational area). This detailed impact assessment shall, at least, address the topics identified in the following paragraphs.

Moreover, in case of a wind farm the detailed impact assessment shall be made for each individual wind turbine and globally for all the visible wind turbines of the wind farm as the global impact may not be equal to the sum of the individual impacts.

As a summary, the detailed engineering assessment is a complex and lengthy process; it requires identifying a large number of cases corresponding to different parameter values each of them corresponding to different external conditions (wind speed and direction, terrain configuration, etc.). Therefore it is recommended to avoid impacting operational areas or to remain within the simple assessment conditions in order to facilitate the impact assessment and the discussions between the ANSP and the wind energy developer.

At this stage, a more accurate assessment of the visibility of the wind turbines by the radars may be undertaken, to concentrate the detailed assessment efforts on the relevant issues.

The following paragraphs specify the requirements that shall be included, as a minimum, in the detailed engineering assessment statement of work.

### **4.4.2 PSR shadowing**

The detailed assessment shall include:

- A calculation of the (two-way) attenuation caused by the wind turbines in three dimensions
- The impact in the three dimensions of this attenuation on the radar detection performance.

The detailed assessment shall address this topic in terms of impact on the PSR probability of detection.

#### **4.4.3 PSR false target reports (due to echoes caused by wind turbines)**

The detailed assessment should include:

- A calculation of the amount of energy reflected back to the radar by the wind turbine taking into account:
  - Different nacelle orientations,
  - Different blade orientations,
  - Different radar frequencies,
  - Different surface conditions (wet, moisture, etc), materials, etc are correctly incorporated in the study,
  - The different elements of the wind turbine located at different heights,
  - Appropriate terrain attenuation calculation based on the use of an agreed tool using appropriate parameters.
- The impact of this energy in terms of false target reports taking into account:
  - Radar receiver capability,
  - Radar signal processing capability,
  - Radar data processing capability

If some of the above aspects cannot be taken into account in a reliable way, it may be agreed by all parties to replace them by mutually agreed assumptions (e.g. worst case).

The detailed assessment shall address this topic and assess the region where these false target reports may appear and their density.

#### **4.4.4 PSR false target reports (due to secondary or indirect reflections from the wind turbines)**

In addition to the case reported above, another potential mechanism providing spurious false target reports is through reflection of true target echoes on wind turbines and through reflection of wind turbine echoes on aircraft.

Four different cases of reflections may happen; they are summarised below and are further described in Annex - C.

True aircraft echoes reflected from the wind turbine: aircraft located in the vicinity of a wind turbine (for cases 1 and 2) or in the vicinity of the radar (only for case 2) will produce a genuine target report at their actual position and may produce a reflected target report in the azimuth of the wind turbine.

Wind turbine echoes reflected to the aircraft: aircraft located in the vicinity of a wind turbine or radar (both cases 3 and 4) will produce a genuine target report at their actual position and may produce a second, reflected target report in the azimuth of the aircraft.

The different cases (1, 2, 3 and 4) and examples of calculation based on simplified equations are provided in Annex - C.

The detailed assessment of false target reports due to reflections shall include:

- A calculation of the aircraft locations where reflections can occur.
- A calculation of where the corresponding false target reports due to reflections will be located.

#### **4.4.5 PSR range and azimuth errors**

When there is a small path difference between the direct and reflected signals the received signal will be a combination of both, which can result in a range and/or bearing measurement error.

In the case where there is a large path difference the two can be separated, which can lead to a false target - as discussed in paragraph 4.4.4 (reflection case).

This effect may occur to targets located further away than the wind turbine and in the same azimuth region.

The detailed assessment shall address this topic and assess the region where these errors may occur and the impact on PSR position accuracy performance in this region.

#### **4.4.6 PSR processing overload**

When PSR is including a plot extractor and/or a mono-radar tracker there will be a limitation in the number of inputs that it can process. If the number of PSR echoes due to wind turbines (clutter and reflections) is too high, the plot processor may need to apply anti-overload techniques. Similarly, if the number of false plots due to wind turbines is too high, the tracker may need to apply overload prevention techniques. Both may have an operational impact (e.g. reducing the operational capability of the radar).

The detailed assessment shall address this topic.

It is to be noted that in this case the affected areas do not depend on where the wind turbines are located but on the internal design of the system (i.e. the applied overload prevention techniques).

It is assumed that the next stages of the surveillance chain (e.g. communication network and multi-sensor tracker) are compatible with the maximum PSR output capacity.

#### **4.4.7 PSR raised thresholds**

In addition to the generation of false target reports the amount of energy reflected back to the radar by the wind turbine (see paragraph 4.4.3 above) will have an impact on the radar CFAR.

The detailed assessment shall address this topic in terms of impact on the PSR probability of detection.

#### **4.4.8 PSR receiver saturation**

In certain cases, the amount of energy reflected back to the radar from the wind turbine (see paragraph 4.4.3 above) can be so large that it saturates the radar receiver.

The detailed assessment shall address this topic in terms of impact on the PSR probability of detection.

#### **4.4.9 SSR Probability of detection and probability of Mode A and Mode C code detection**

If a wind turbine is located close to an SSR, the detection of aircraft located close to the wind turbine and within the same azimuth may be impacted. The impact shall be calculated in the three dimensions independently for the uplink (aircraft located in the shadow region behind the wind turbine) and the downlink transmissions (SSR located in the shadow region behind the wind turbine). In the case of the downlink transmission, the aircraft position detection may not be affected whereas the Mode A or Mode C code detection may be affected.

The detailed assessment shall address this topic and shall predict the impact in the 3 dimensions on position detection and Mode A and C code detection performance.

#### **4.4.10 SSR false target reports**

Most SSR systems build up maps of static reflectors (e.g. tower, buildings) to reject reflected replies; but because wind turbines are not seen as static objects, this technique is not as efficient.

Therefore SSR false target reports may appear due to reflection on the wind turbine of the uplink signal, of the downlink signal and/or of both.

The detailed assessment shall address this topic and shall predict where the false target reports will be located.

#### **4.4.11 SSR 2D position accuracy**

SSR bearing errors may occur when there is a small path difference between the direct and reflected signals. In the case where there is a large path difference the two can be separated which can lead to a false target - as discussed in paragraph 4.4.10.

Effects can be seen in MSSR, Mode S and classical 'sliding window' SSR systems.

An MSSR or Mode S system calculates the bearing of an aircraft using the orientation of the EM wave as it reaches the antenna. Reflections of the transponder signal from nearby objects (such as wind turbines) will combine with the direct signal in such a way that the wave-front is distorted. This can lead to errors in the bearing calculation.

In sliding window systems, the reflected energy arriving back at the antenna will be dispersed in azimuth, such that it is no longer centred on the true target azimuth. This will 'fool' the algorithms used by many SSRs to determine azimuth, and an error will occur.

Under these conditions (small path difference) range measurement errors may also occur due to the combination of the direct and reflected signals and the measurement of the time of arrival of the SSR reply may be altered.

This effect may occur to targets located further away than the wind turbine and in the same azimuth region.

The detailed assessment shall address this topic and shall predict the impact in the 3 dimensions on the SSR position accuracy performance.

It is to be noted that in case of a Mode S radar a single reply is sufficient to generate a target report.

## **4.5 Operational assessment**

### **4.5.1 Generalities**

Once an adverse engineering impact has been predicted, the next phase will be to assess whether this effect will be operationally tolerable or not. The process can be made quicker if certain 'ground rules' can be established, or areas of known sensitivity are published in advance which precludes the need for engineers to approach ATC operational staff. Certain applications may have such dramatic effects that the need to enter a dialogue with ATC is nugatory. However, the majority of cases will normally involve discussions with ATC Operations representatives who are familiar with the airspace being affected and/or Human Factors specialists.

### **4.5.2 PSR Probability of detection**

The operational assessment will be based on the location of the affected 3D zones with respect to the operational volume of airspace and the criticality of the PSR surveillance information in these zones.

### **4.5.3 PSR false target reports**

The operational assessment will be based on the location of the false target reports due to the presence of the wind turbines with respect to the operational volume of airspace.

### **4.5.4 PSR 2D position accuracy**

The operational assessment will be based on the location of the affected 2D zones with respect to the operational volume of airspace and the criticality of the PSR surveillance information in these zones.

### **4.5.5 PSR plot/track processing capacity**

The operational assessment will be based on the location of the affected 2D zones with respect to the operational volume of airspace and the criticality of the PSR surveillance information in these zones.

### **4.5.6 SSR probability of detection**

The operational assessment will be based on the location of the affected 3D zones with respect to the operational volume of airspace and the criticality of the SSR surveillance information in these zones.

### **4.5.7 SSR false target reports**

The operational assessment will be based on the location of the false target reports due to the presence of the wind turbines with respect to the operational volume of airspace.

#### **4.5.8 SSR 2D position accuracy**

The operational assessment will be based on the location of the affected 2D zones with respect to the operational volume of airspace.

## 4.6 Possible mitigations

### 4.6.1 Generalities

It may be possible that a certain amount of reduced performance is tolerable, either because it is in an area of minimal concern to the end user or sufficient operational procedures are in place to address any surveillance short fall.

Otherwise, in order to accommodate the wind turbine application, mitigation options may be investigated. The following options should be considered individually and/or in combination:

1. Wind energy developer mitigations: Can the wind turbine proposal be modified to eradicate or minimise the effects on ATC surveillance systems and operations?
2. ANSP technical mitigations: Can the sensor and/or surveillance system architecture be modified or configured to accommodate the wind energy project to within a level of tolerable degradation of service to ATC?
3. ANSP operational mitigations: Can ATC modify procedures to accommodate the expected reduction in surveillance quality?

An important consideration for choosing the mitigation options should be maintenance of ATC safety and cost-effectiveness, while at the same time taking into account that the global project (wind energy and associated mitigations) should result in an overall net reduction in carbon over an agreed time period.





#### 4.6.2 Mitigation option table

The table below lists different mitigation options that may be applied alone or in combination with others. The table provides for every mitigation option the issues that it can potentially solve.

| Applicable to                       | Mitigation option                                  | When mitigation could be applied    |                                     |                                     |                                     |                |                   |                       | Consideration regarding the mitigation option                        |
|-------------------------------------|--|-------------------------------------|-------------------------------------|-------------------------------------|-------------------------------------|----------------|-------------------|-----------------------|--|
|                                     |  | Lack of PSR Pd                      | PSR false targets                   | PSR position accuracy i             | Overload of PSR capacities          | Lack of SSR Pd | SSR false targets | SSR position accuracy |  |
| Non cooperative surveillance sensor | Blank PSR transmission in an azimuth sector        |                                     | <input checked="" type="checkbox"/> |                                     | <input checked="" type="checkbox"/> |                |                   |                       | May need to be combined with in-fill PSR/MSPSR in blanked sector(s). |
|                                     | Suppress PSR radar returns in range-azimuth sector |                                     | <input checked="" type="checkbox"/> |                                     | <input checked="" type="checkbox"/> |                |                   |                       | May need to be combined with in-fill PSR/MSPSR in blanked sector(s). |
|                                     | Improve PSR anti wind turbine clutter capabilities |                                     | <input checked="" type="checkbox"/> |                                     | <input checked="" type="checkbox"/> |                |                   |                       |  |
|                                     | Strengthen primary track initiation conditions     |                                     | <input checked="" type="checkbox"/> |                                     |                                     |                |                   |                       | At mono-radar tracker or at multi-sensor tracker level.              |
|                                     | Adapt PSR overload prevention facilities           |                                     |                                     |                                     | <input checked="" type="checkbox"/> |                |                   |                       |  |
|                                     | Upgrade PSR processing capabilities                |                                     |                                     |                                     | <input checked="" type="checkbox"/> |                |                   |                       |  |
|                                     | Upgrade PSR output interface capabilities          |                                     |                                     |                                     | <input checked="" type="checkbox"/> |                |                   |                       |  |
|                                     | In-fill PSR  | <input checked="" type="checkbox"/> | <input checked="" type="checkbox"/> | <input checked="" type="checkbox"/> |                                     |                |                   |                       |  |
|                                     | In-fill MSPSR                                      | <input checked="" type="checkbox"/> | <input checked="" type="checkbox"/> | <input checked="" type="checkbox"/> |                                     |                |                   |                       | Provided that MSPSR concept is validated.                            |

| Applicable to                   | Mitigation option  | When mitigation could be applied    |                                     |                                     |                                     |                                     |                                     |                                     | Consideration regarding the mitigation option  |
|---------------------------------|--|-------------------------------------|-------------------------------------|-------------------------------------|-------------------------------------|-------------------------------------|-------------------------------------|-------------------------------------|--|
|                                 |  | Lack of PSR Pd                      | PSR false targets                   | PSR position accuracy i             | Overload of PSR capacities          | Lack of SSR Pd                      | SSR false targets                   | SSR position accuracy               |  |
| Cooperative surveillance system | Blank SSR transmission in an azimuth sector              |                                     |                                     |                                     |                                     |                                     | <input checked="" type="checkbox"/> | <input checked="" type="checkbox"/> | May need to be combined with in-fill SSR/WAM/ADS-B in blanked sector(s)  |
|                                 | In-fill SSR  |                                     |                                     |                                     |                                     | <input checked="" type="checkbox"/> | <input checked="" type="checkbox"/> | <input checked="" type="checkbox"/> |  |
|                                 | In-fill WAM <sup>5</sup>                                 |                                     |                                     |                                     |                                     | <input checked="" type="checkbox"/> | <input checked="" type="checkbox"/> | <input checked="" type="checkbox"/> |  |
|                                 | In-fill ADS-B <sup>5</sup>                               |                                     |                                     |                                     |                                     | <input checked="" type="checkbox"/> | <input checked="" type="checkbox"/> | <input checked="" type="checkbox"/> | Provided that aircraft are ADS-B equipped  |
|                                 | Improve SSR anti-reflection capabilities                 |                                     |                                     |                                     |                                     |                                     | <input checked="" type="checkbox"/> |                                     | At SSR level and/or at multi-sensor level  |
| Operation                       | Move ATC route   | <input checked="" type="checkbox"/> | <input checked="" type="checkbox"/> | <input checked="" type="checkbox"/> |                                     | <input checked="" type="checkbox"/> |                                     | <input checked="" type="checkbox"/> |  |
|                                 | Change airspace classification or apply MTZ <sup>6</sup> | <input checked="" type="checkbox"/> | <input checked="" type="checkbox"/> | <input checked="" type="checkbox"/> |                                     |                                     |                                     |                                     | Note that PSR may still be required to detect aircraft without a functioning SSR Transponder.  |
| Wind turbine                    | Move wind turbines out of radar line of sight            | <input checked="" type="checkbox"/> | <input checked="" type="checkbox"/> | <input checked="" type="checkbox"/> | <input checked="" type="checkbox"/> | <input checked="" type="checkbox"/> | <input checked="" type="checkbox"/> | <input checked="" type="checkbox"/> |  |
|                                 | Move wind turbines out of critical areas                 | <input checked="" type="checkbox"/> | <input checked="" type="checkbox"/> | <input checked="" type="checkbox"/> |                                     | <input checked="" type="checkbox"/> | <input checked="" type="checkbox"/> | <input checked="" type="checkbox"/> |  |
|                                 | Change wind farm layout                                  | <input checked="" type="checkbox"/> |                                     |                                     |                                     |                                     |                                     |                                     | Affects Region 2 only, see § 4.3.1.  |
|                                 | Reduce number of wind turbines in radar line of sight    |                                     |                                     |                                     | <input checked="" type="checkbox"/> |                                     |                                     |                                     |  |
|                                 | Reduce wind turbine radar reflectivity                   |                                     | <input checked="" type="checkbox"/> |                                     | <input checked="" type="checkbox"/> |                                     | <input checked="" type="checkbox"/> |                                     | If wind turbine is in radar line of sight of several radars, the mitigation is only applicable if they operate in the same frequency band. |

**Table 3: Mitigation options**

<sup>5</sup> This version of the guidelines does not address the assessment of wind turbine impacts on WAM or ADS-B.

<sup>6</sup> Mandatory Transponder Zone: a portion of the airspace where all aircraft are required to be equipped with a transponder.

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## 5 REFERENCES AND ACRONYMS

### 5.1 Referenced documents

- [RD 1]** EUROCONTROL Standard for Surveillance in En-route Airspace and Major Terminal Areas – SUR.ET1.ST01.1000-STD-01-01 dated March 1997 edition 1.0  
<http://www.eurocontrol.int/surveillance/gallery/content/public/documents/SURVSTD.pdf>
- [RD 2]** ICAO Annex 10 Volume IV 4<sup>th</sup> edition July 2007
- [RD 3]** ICAO European Guidance Material on Managing Building Restricted Areas Second Edition 2009 ICAO EUR Doc 015  
[http://www.paris.icao.int/documents\\_open/show\\_file.php?id=188](http://www.paris.icao.int/documents_open/show_file.php?id=188)
- [RD 4]** ICAO Procedures for Air Navigation Services Air Traffic Management (PANS ATM) Doc 4444 ATM/501 Fifteenth Edition 2007
- [RD 5]** EUROCONTROL Regulatory and Advisory Framework – Regulatory Provisions dated November 2005 Edition 3.0 ERAF/04-002/3.0  
[http://www.eurocontrol.int/enprm/gallery/content/public/docs/eraf\\_04\\_002\\_v\\_3\\_0.pdf](http://www.eurocontrol.int/enprm/gallery/content/public/docs/eraf_04_002_v_3_0.pdf)
- [RD 6]** EUROCONTROL Regulatory and Advisory Framework – Advisory Material dated November 2005 Edition 3.0 ERAF/04-002/ADV/3.0  
[http://www.eurocontrol.int/enprm/gallery/content/public/docs/eraf\\_04\\_002\\_adv\\_v\\_3\\_0.pdf](http://www.eurocontrol.int/enprm/gallery/content/public/docs/eraf_04_002_adv_v_3_0.pdf)

## 5.2 List of acronyms

| Acronym | Definition  |
|---------|---|
| ADS-B   | Automatic Dependent Surveillance - Broadcast                        |
| ANSP    | Air Navigation Service Provider                                     |
| ATC     | Air Traffic Control   |
| ATM     | Air Traffic Management  |
| BRA     | Building Restricted Areas   |
| CFAR    | Constant False Alarm Rate (primary radar technique)                 |
| DTED    | Digital Terrain Elevation Data                                      |
| EC      | European Commission   |
| EM      | Electro Magnetic  |
| ERAF    | EUROCONTROL Regulatory and Advisory Framework                       |
| FFM     | Far-Field Monitor   |
| ICAO    | International Civil Aviation Organisation                           |
| IFR     | Instrument Flight Rules   |
| MDS     | Minimum Discernable Signal  |
| MLAT    | Multi LATeration  |
| MSPSR   | Multi Static Primary Surveillance Radar                             |
| MSSR    | Monopulse Secondary Surveillance Radar                              |
| MTD     | Moving Target Detector (primary radar technique)                    |
| MTI     | Moving Target Indicator (primary radar technique equivalent to MTD) |
| MTZ     | Mandatory Transponder Zone  |
| NSA     | National Supervisory Authority                                      |
| PSR     | Primary Surveillance Radar  |
| RCS     | Radar Cross Section   |
| RF      | Radio Frequency   |
| Rx      | Receiver  |
| SES     | Single European Sky   |
| SESAR   | Single European Sky ATM Research                                    |
| SLA     | Service Level Agreement   |
| SSR     | Secondary Surveillance Radar  |
| STC     | Sensitivity Time Control (primary radar technique)                  |
| Tx      | Transmitter   |
| UNFCCC  | United Nations Framework Convention on Climate Change               |
| WAM     | Wide Area Multilateration   |
| WGS84   | World Geodetic System 1984  |

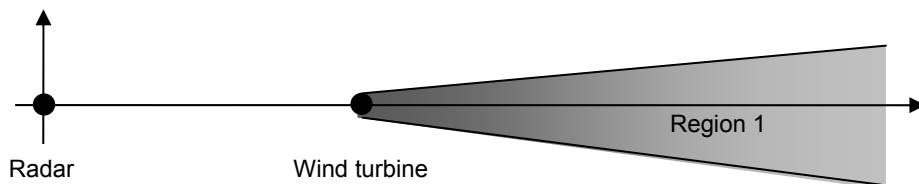
**Table 4: Acronym list**

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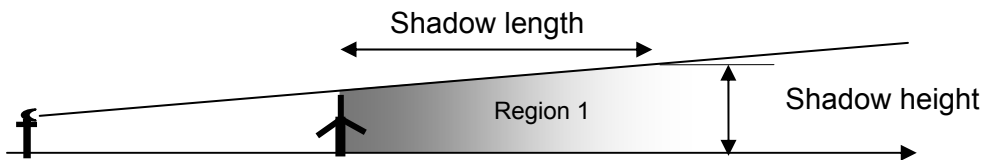
## ANNEX - A PSR reduction of probability of detection – Assessment of Region 1 dimensions

### A - 1 Introduction

When a turbine lies directly between the transmitting and receiving antenna the strength of the signal reaching the receiver is lower than it would otherwise be. When the transmitter and/or receiver are part of the surveillance sensor under assessment the shape and severity of this 'shadow region' will determine the impact of the turbine on how the equipment can be used. In the case of the PSR it is considered that region 1 extends up to the PSR maximum range. The basic features of the shadow are:



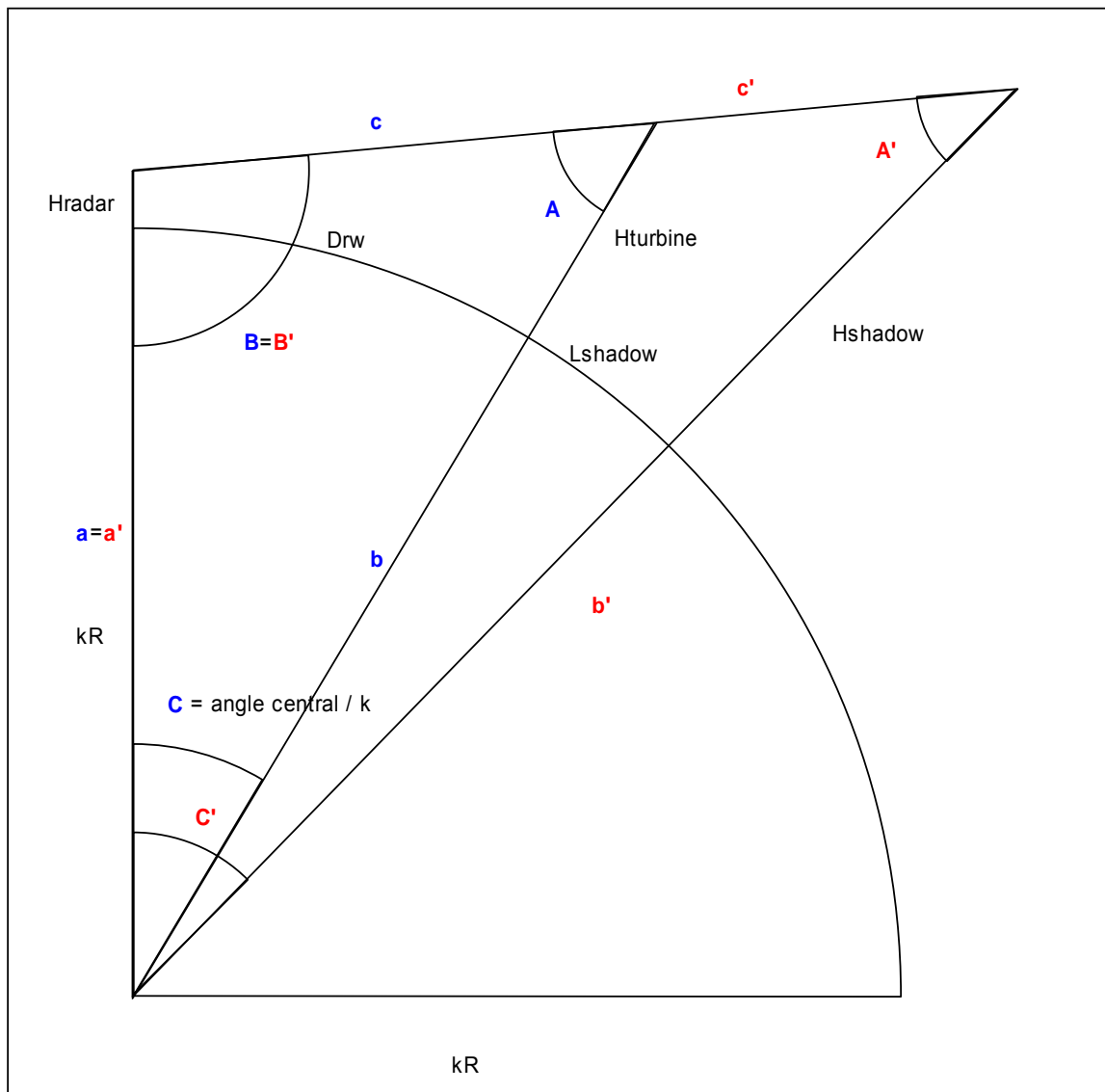
**Figure 9: Top-view of wind turbine shadow**



**Figure 10: Side-view of wind turbine shadow**

### A - 2 Shadow Height

The shadow height is calculated by simply considering the geometry of the wind turbine and the transmitter as shown on Figure 10 above, taking into account the maximum height of the turbine, the earth curvature (see Figure 11 below), the earth radius (R) and the fact that EM waves do not propagate in straight line above earth, therefore a factor k (typically 4/3) is applied to calculate the central angle.



**Figure 11: Principle of shadow height calculation**

Taking into account that:

$$a = k.R + H_{radar}$$

$$b = k.R + H_{turbine}$$

$$c = \sqrt{a^2 + b^2 - 2.a.b.\cos(C)}$$

$$B = \text{Arc cos}((a^2 - b^2 + c^2) / 2.a.c)$$

$$C = D_{rw} / k.R$$

$$C' = \frac{D_{rw} + L_{shadow}}{R.k}$$

$$B' = B$$

$$A' = \pi - B' - C'$$

$$b' = a'.\sin(B')/\sin(A')$$

Where  $D_{rw}$  is the distance between the radar and the wind turbine,  $R$  is the radius of the earth and  $L_{shadow}$  is the length of the shadow zone.

The height of the shadow zone can be calculated as follow:

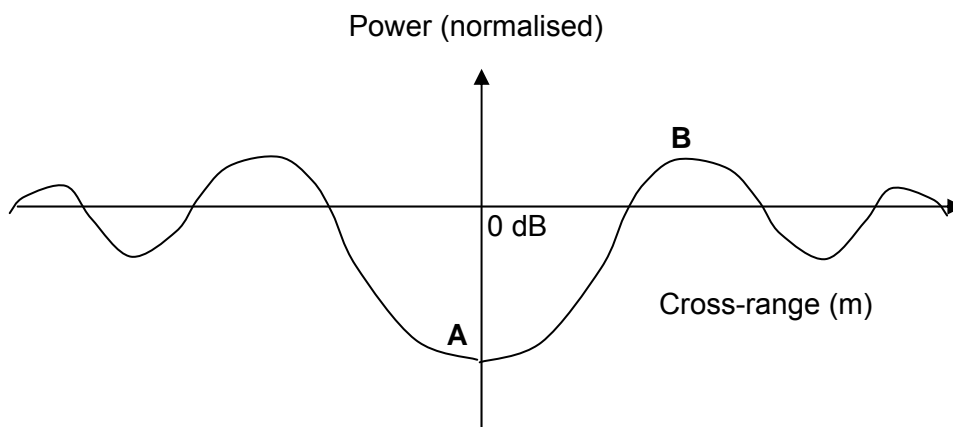
$$H_{shadow} = b' - k.R \quad \text{Equation 1}$$

The symbols used in this Annex have the following meanings

|               |  |
|---------------|--|
| $R$           | The radius of the earth (m) at the position of the radar   |
| $H_{radar}$   | Geodetic height of the radar (m)   |
| $H_{turbine}$ | Geodetic height of the wind turbine (m)  |
| $H_{shadow}$  | Geodetic height of the shadow of the wind turbine at shadow length (m)                                       |
| $L_{shadow}$  | Shadow length (m)  |
| $k$           | Factor (typically 4/3) to take into account that EM waves do not propagate in straight line above the earth. |
| $D_{rw}$      | Distance radar to wind turbine (m)   |

### A - 3 Shadow Width

Figure 9 above shows a very simplistic representation of the shadow width, it is possible to calculate a more realistic estimate using the following argument. A typical cross-range section of the shadow effect is shown in the following Figure 12 where a reflection from a metallic object is assumed; hence the direct and reflected signals will be in anti-phase.

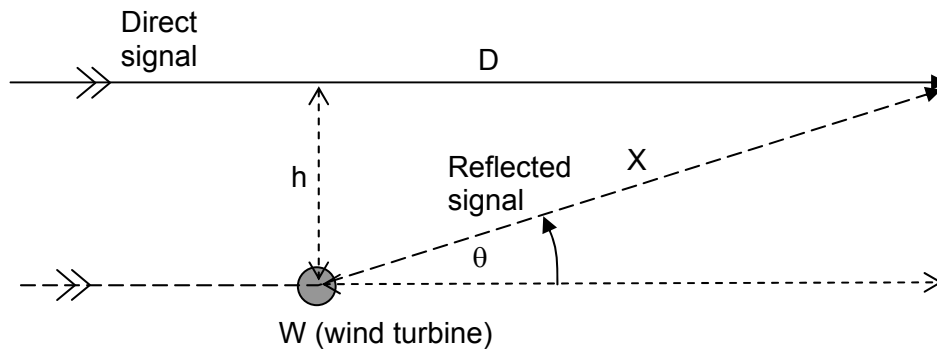


**Figure 12: Diagram of a cross-section of a shadow**



At point "A" the path difference is zero and so the signals combine de-constructively causing the deepest shadow; at point "B", where path difference =  $\lambda/2$ , they combine constructively to give a maxima. Note that successive maxima are odd multiples of  $\lambda/2$ , where path difference =  $(2n+1)\lambda/2$ . The maxima get weaker because the interfering signal is weaker at larger angles off the forward-scatter direction.

A conservative estimate of shadow width is the locus of points formed by point B as a function of down-range; the geometry is as shown in Figure 13 below:



**Figure 13: Path difference geometry for shadow width calculation**

The path difference,  $\Delta$ , between the direct and reflected signals at the receiver is given by:

$$\Delta = X - D = \sqrt{h^2 + D^2} - D \quad \text{Equation 2}$$

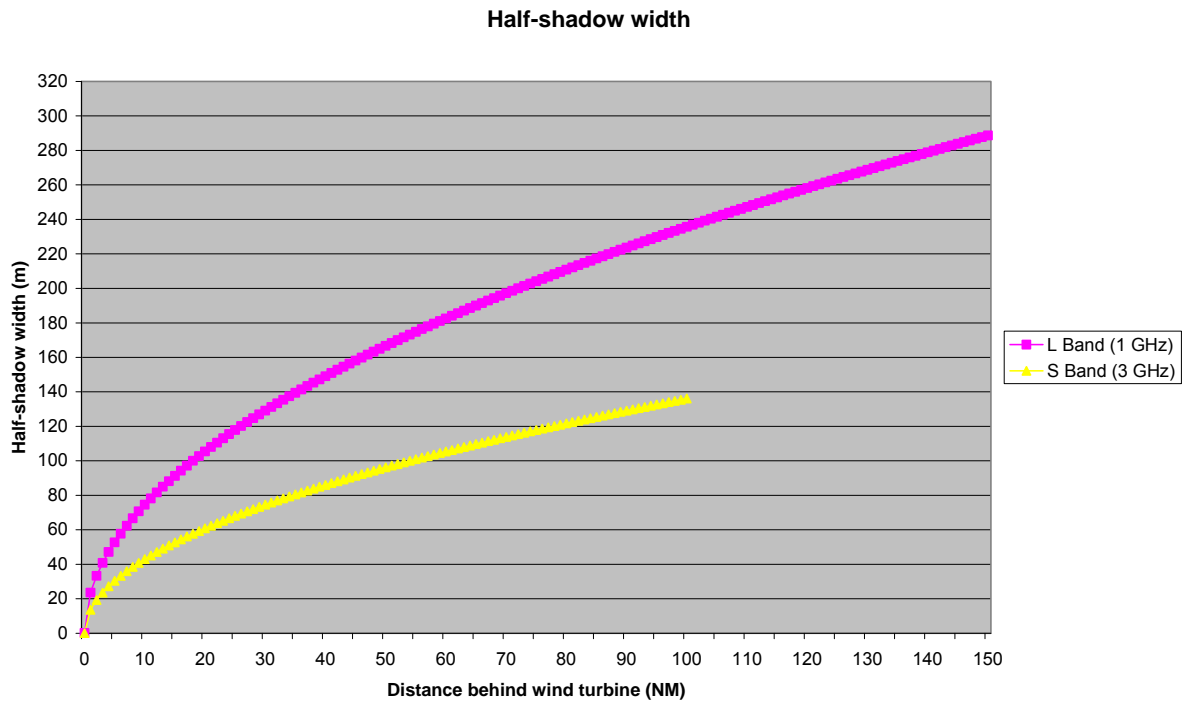
and so the locus of points which define the width of the shadow at a distance D beyond the turbine is found by setting path difference =  $\lambda/2$  and solving for the half-width, h:

$$\frac{\lambda}{2} = \sqrt{h^2 + D^2} - D \quad \text{Equation 3}$$

$$h = \sqrt{\left(\frac{\lambda}{2} + D\right)^2 - D^2} \quad \text{Equation 4}$$

If  $\lambda$  is much smaller than D, which is the case here, Equation 4 can be simplified:

$$h = \sqrt{\lambda \cdot D} \quad \text{Equation 5}$$



**Figure 14: Half-shadow width as a function of D**

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## ANNEX - B PSR Equations (no reflection)

### B - 1 Basic Radar Equation

In normal PSR operation, the power reflected back from the wind turbine will be equal to:

$$P_{ref} = \frac{\sigma \cdot F^2 \cdot G_t \cdot P_t \cdot G_r \cdot \lambda^2}{(4 \cdot \pi \cdot)^3 \cdot D^4} \quad \text{Equation 6}$$

where the symbols have the following meanings

|           |  |
|-----------|--|
| $P_{ref}$ | The power of the reflected signal arriving at the radar (W)            |
| $P_t$     | Transmitted power  |
| $G_t$     | Transmit antenna gain  |
| $G_r$     | Receive antenna gain   |
| $\sigma$  | The mono-static RCS of the wind turbine <sup>7</sup> (m <sup>2</sup> ) |
| $F$       | Terrain induced attenuation factor between radar and wind turbine.     |
| $D$       | Distance radar to wind turbine (m)                                     |
| $\lambda$ | Signal wavelength (m)  |

### B - 2 Further Processing

Whilst at its most basic the remainder of the radar can be modelled as a simple threshold detector by comparing  $P_{ref}$ , above, to a defined threshold for the radar under test this is a huge simplification for a modern radar system.

Other than to state that where possible as much of the radars internal processing should be taken into account, it is not intended to go further within this document as data processing varies so widely from radar to radar and the relevant algorithms are often difficult to obtain or model. Some of the issues which may affect the probability of wind turbine detection include the following items:

- **Sliding window** - Most systems determine detection using a statistical M detections from N pulses algorithm.
- **MTI-MTD Filtering** – Most PSR systems now employ MTI or MTD to discard returns from stationary objects based on Doppler filtering.
- **Tracking Algorithms** - Plot-extracted systems will only provide plot information should a series of echoes over a number of scans pass certain tracking criteria.

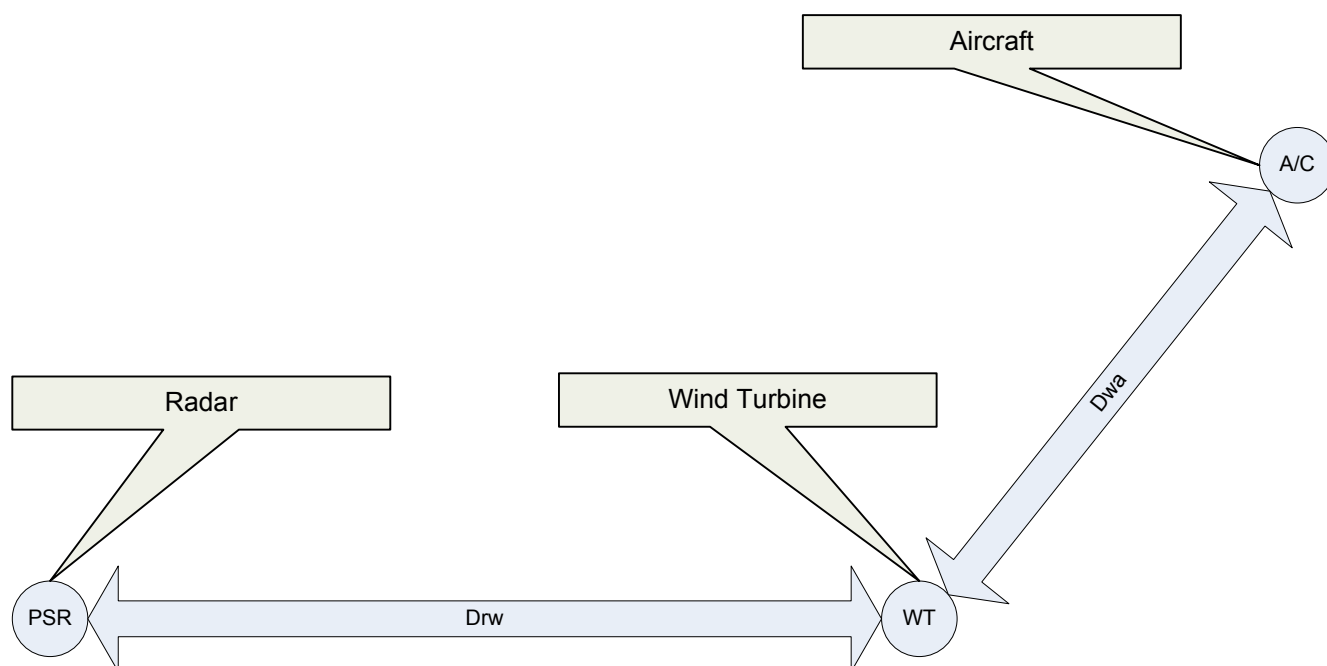
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<sup>7</sup> The radar cross section of the wind turbine, although the term is not fully relevant because the wind turbine is not in free space but put on the ground, represents the fraction of EM power transmitted by the radar that is reflected back (mono-static) or scattered in another direction (bi-static) by the wind turbine. This parameter depends a lot on the attitude of the wind turbine with respect to the direction of the EM wave transmitted by the radar, in particular on the orientation of the nacelle and on the orientation of the blades that are varying in accordance with the wind conditions. Furthermore in the case of the bi-static RCS, it depends on the considered directions (incidental and scattered)

## ANNEX - C PSR Equations (reflection)

### C - 1 Radar Equations in case of reflected signals

There are 4 cases of configuration radar/wind turbine/aircraft where additional echoes due to reflected signal can be detected by the radar. They are illustrated on Figure 15 to Figure 18.



**Figure 15: PSR reflection case 1**

In case 1, the reflection is located in the azimuth of the wind turbine, the reflected signal is received through the radar antenna main beam.

In this case, the power reflected back will be equal to:

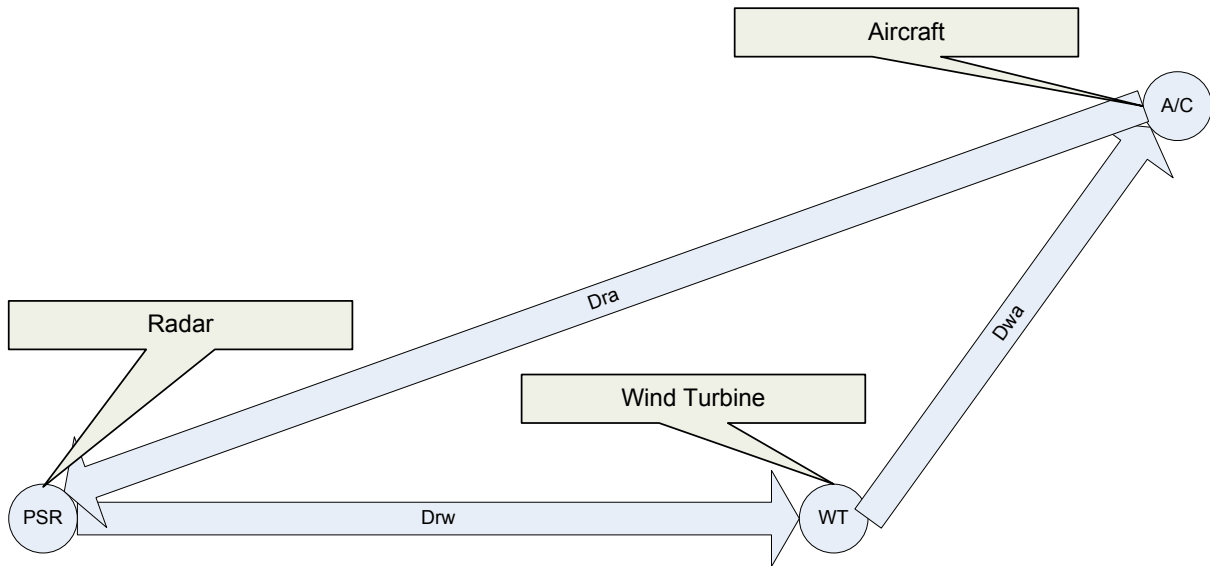
$$P_{ref} = \frac{\sigma_a \cdot \sigma_{w1} \cdot \sigma_{w2} \cdot F_{rw}^2 \cdot F_{wa}^2 \cdot G_t \cdot P_t \cdot G_r \cdot \lambda^2}{(4 \cdot \pi)^5 \cdot D_{rw}^4 \cdot D_{wa}^4} \quad \text{Equation 7}$$

Comparing this power to the radar receiver detection threshold one can derive the volume around a wind turbine where aircraft must be located to cause a reflection.

$$R_1 = \sqrt[4]{\frac{\sigma_a \cdot \sigma_{w1} \cdot \sigma_{w2} \cdot F_{rw}^2 \cdot F_{wa}^2 \cdot G_t \cdot P_t \cdot G_r \cdot \lambda^2}{(4 \cdot \pi)^5 \cdot D_{rw}^4 \cdot P_{thresh}}} \quad \text{Equation 8}$$

Worst case estimation can be calculated assuming  $F_{rw} = F_{wa} = 1$ ,  $G_t = G_r = G$  and  $\sigma_{w1} = \sigma_{w2} = \sigma_w$ .

$$R_1 = \sqrt[4]{\frac{\sigma_a \cdot \sigma_w^2 \cdot G^2 \cdot P_t \cdot \lambda^2}{(4 \cdot \pi)^5 \cdot D_{rw}^4 \cdot P_{thresh}}} \quad \text{Equation 9}$$



**Figure 16: PSR reflection case 2**

In case 2, the reflection is located in the azimuth of the wind turbine, the reflected signal is received through the radar antenna sidelobes.

In this case, the power reflected back will be equal to:

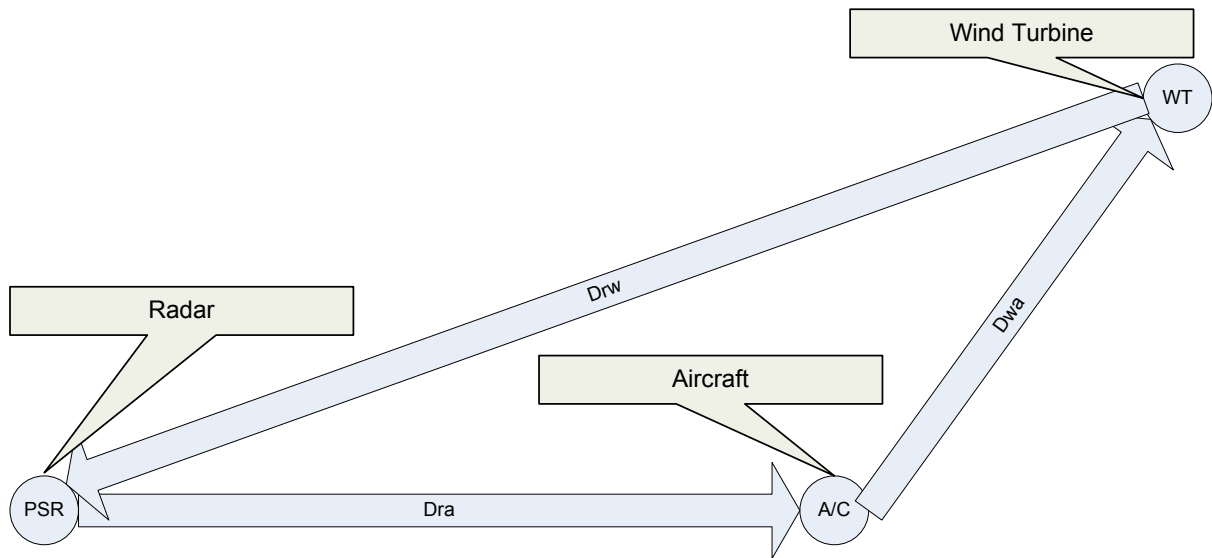
$$P_{ref} = \frac{\sigma_{a2} \cdot \sigma_{w1} \cdot F_{rw} \cdot F_{wa} \cdot F_{ar} \cdot G_t \cdot P_t \cdot G_{rs} \cdot \lambda^2}{(4 \cdot \pi)^4 \cdot D_{rw}^2 \cdot D_{wa}^2 \cdot D_{ra}^2} \quad \text{Equation 10}$$

Comparing this power to the radar receiver detection threshold one can derive the volume around a wind turbine where aircraft must be located to cause a reflection.

$$R_2 = \sqrt[2]{\frac{\sigma_{a2} \cdot \sigma_{w1} \cdot F_{rw} \cdot F_{wa} \cdot F_{ar} \cdot G_t \cdot P_t \cdot G_{rs} \cdot \lambda^2}{(4 \cdot \pi)^4 \cdot D_{rw}^2 \cdot D_{ra}^2 \cdot P_{thresh}}} \quad \text{Equation 11}$$

Worst case estimation can be calculated assuming  $F_{rw} = F_{wa} = F_{ar} = 1$ ,  $\sigma_{a2} = \sigma_a$  and  $\sigma_{w1} = \sigma_w$ .

$$R_2 = \sqrt[2]{\frac{\sigma_a \cdot \sigma_w \cdot G_t \cdot P_t \cdot G_{rs} \cdot \lambda^2}{(4 \cdot \pi)^4 \cdot D_{rw}^2 \cdot D_{ra}^2 \cdot P_{thresh}}} \quad \text{Equation 12}$$



**Figure 17: PSR reflection case 3**

In case 3, the reflection is located in the azimuth of the aircraft, the reflected signal is received through the radar antenna sidelobes.

In this case, the power reflected back will be equal to:

$$P_{ref} = \frac{\sigma_{a1} \cdot \sigma_{w2} \cdot F_{ra} \cdot F_{aw} \cdot F_{wr} \cdot G_t \cdot P_t \cdot G_{rs} \cdot \lambda^2}{(4 \cdot \pi)^4 \cdot D_{ra}^2 \cdot D_{wa}^2 \cdot D_{rw}^2} \quad \text{Equation 13}$$

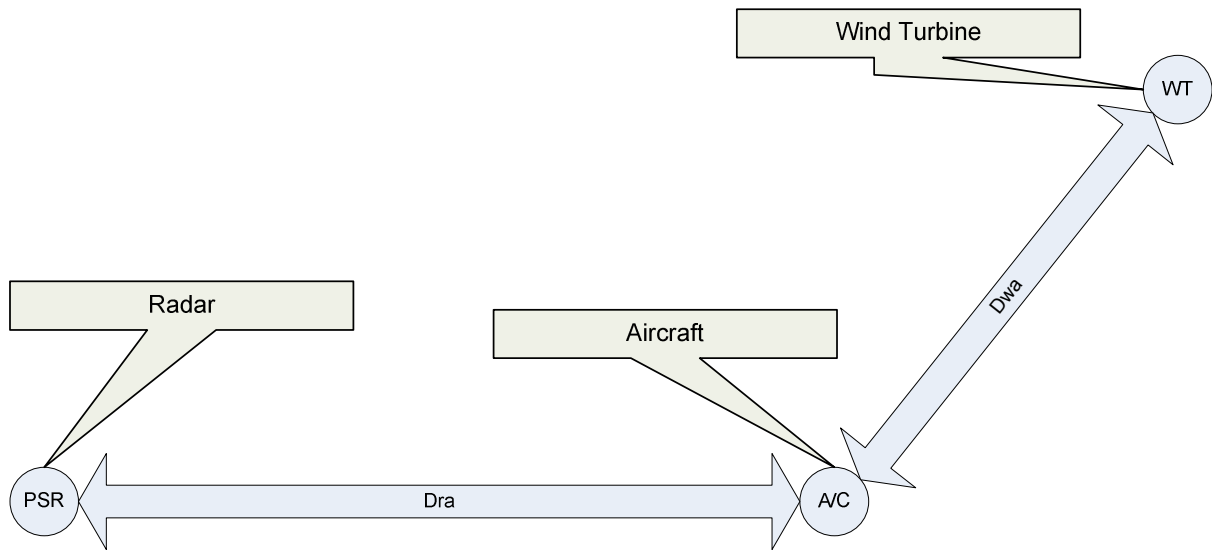
Comparing this power to the radar receiver detection threshold one can derive the volume around a wind turbine where aircraft must be located to cause a reflection.

$$R_3 = \sqrt[2]{\frac{\sigma_{a1} \cdot \sigma_{w2} \cdot F_{ra} \cdot F_{aw} \cdot F_{wr} \cdot G_t \cdot P_t \cdot G_{rs} \cdot \lambda^2}{(4 \cdot \pi)^4 \cdot D_{ra}^2 \cdot D_{rw}^2 \cdot P_{thresh}}} \quad \text{Equation 14}$$

Worst case estimation can be calculated assuming  $F_{ra} = F_{aw} = F_{wr} = 1$ ,  $\sigma_{a1} = \sigma_a$  and  $\sigma_{w2} = \sigma_w$ .

$$R_3 = \sqrt[2]{\frac{\sigma_a \cdot \sigma_w \cdot G_t \cdot P_t \cdot G_{rs} \cdot \lambda^2}{(4 \cdot \pi)^4 \cdot D_{ra}^2 \cdot D_{rw}^2 \cdot P_{thresh}}} \quad \text{Equation 15}$$

Note that there exists a certain volume around the radar and wind turbine where these types (types 2 and 3) of reflections could occur (see Figure 19). There also exists a critical distance between radar and wind turbine for which these volumes start to merge.



**Figure 18: PSR reflection case 4**

In case 4, the reflection is located in the azimuth of the aircraft, the reflected signal is received through the radar antenna main beam.

In this case, the power reflected back will be equal to:

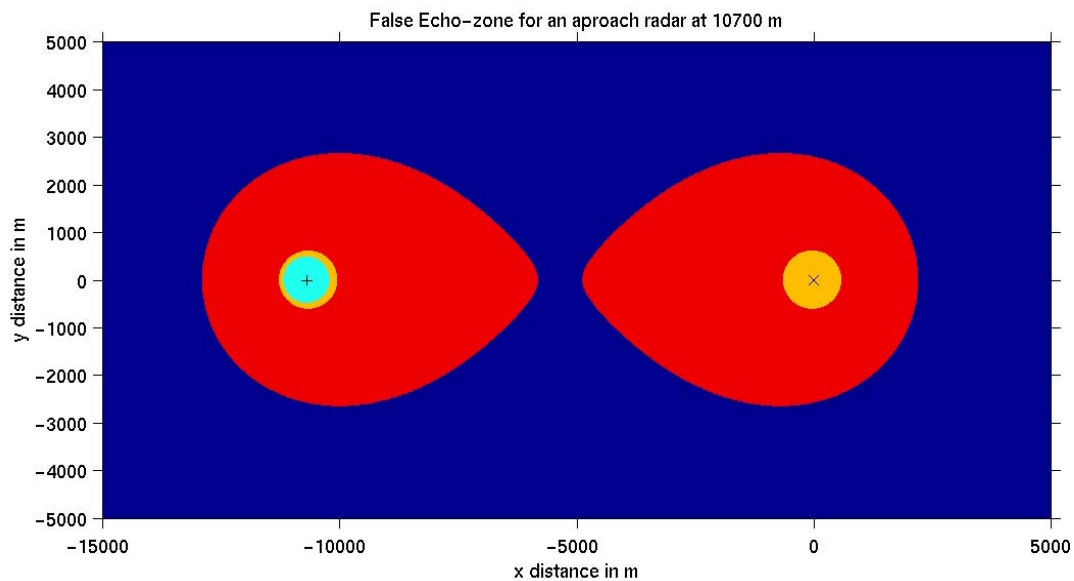
$$P_{ref} = \frac{\sigma_w \cdot \sigma_{a1} \cdot \sigma_{a2} \cdot F_{ra}^2 \cdot F_{aw}^2 \cdot G_t \cdot P_t \cdot G_r \cdot \lambda^2}{(4 \cdot \pi)^5 \cdot D_{ra}^4 \cdot D_{wa}^4} \quad \text{Equation 16}$$

Comparing this power to the radar receiver detection threshold one can derive the volume around a wind turbine where aircraft must be located to cause a reflection.

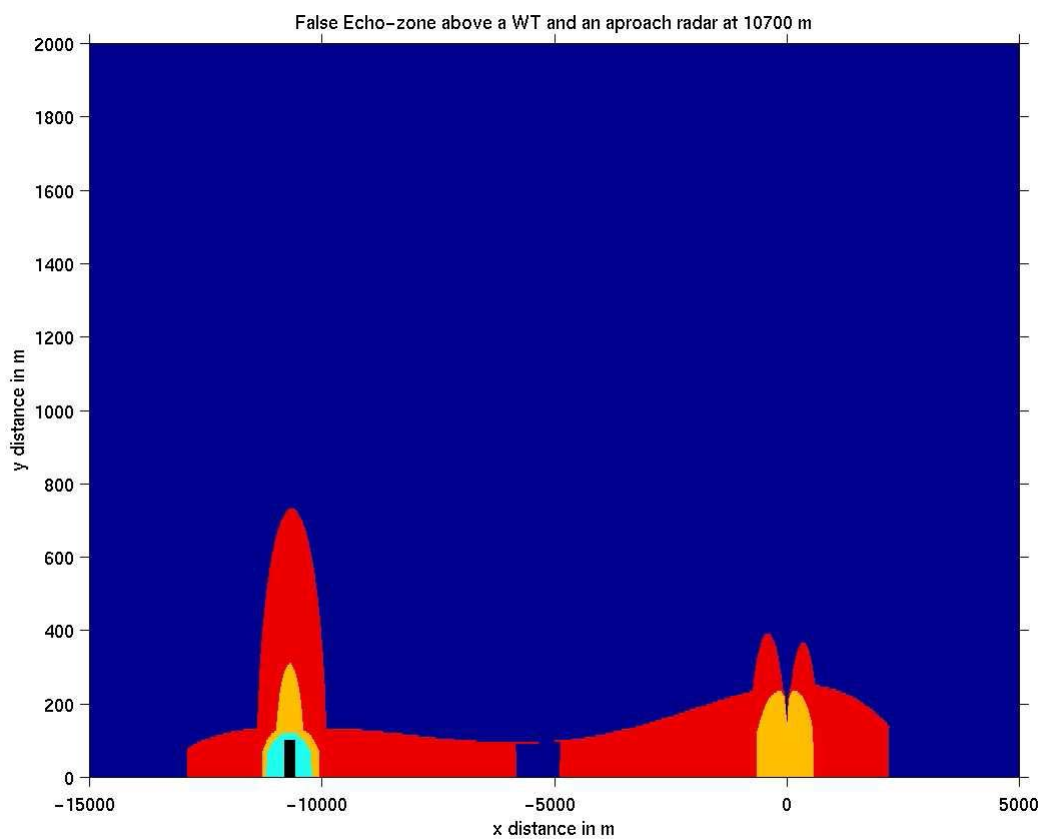
$$R_4 = \sqrt[4]{\frac{\sigma_w \cdot \sigma_{a1} \cdot \sigma_{a2} \cdot F_{ra}^2 \cdot F_{aw}^2 \cdot G_t \cdot P_t \cdot G_r \cdot \lambda^2}{(4 \cdot \pi)^5 \cdot D_{ra}^4 \cdot P_{thresh}}} \quad \text{Equation 17}$$

Worst case estimation can be calculated assuming  $F_{ra} = F_{aw} = 1$ ,  $G_t = G_r = G$  and  $\sigma_{a1} = \sigma_{a2} = \sigma_a$ .

$$R_4 = \sqrt[4]{\frac{\sigma_a^2 \cdot \sigma_w \cdot G^2 \cdot P_t \cdot \lambda^2}{(4 \cdot \pi)^5 \cdot D_{ra}^4 \cdot P_{thresh}}} \quad \text{Equation 18}$$



**Figure 19: Example of calculation of aircraft locations where reflection can occur (horizontal)**



**Figure 20: Example of calculation of aircraft locations where reflection can occur (vertical)**



Figure 19 and Figure 20 provide a typical example of the computation of the different reflection zones (radar location marked with x; wind turbine location marked with +). The cyan area corresponds to aircraft locations where case 1 can happen. The orange areas correspond to aircraft locations where case 4 can happen. The red areas correspond to aircraft locations where case 2 or 3 can happen.

In equations 6 to 17 the symbols have the following meanings

|                   |   |
|-------------------|---|
| $P_{ref}$         | The power of the reflected signal arriving at the radar (W)                         |
| $P_t$             | Transmitted power (W)   |
| $P_{thresh}$      | Radar receiver detection threshold (W)  |
| $G_t$             | Transmit antenna gain   |
| $G_r$             | Receive antenna gain (main beam)  |
| $G_{rs}$          | Receive antenna gain (side lobes)   |
| $\sigma_a$        | The mono-static RCS of the aircraft ( $m^2$ )                                       |
| $\sigma_w$        | The mono-static RCS of the wind turbine <sup>7</sup> ( $m^2$ )                      |
| $\sigma_{a1}$     | The bi-static RCS of the aircraft from radar to wind turbine ( $m^2$ )              |
| $\sigma_{a2}$     | The bi-static RCS of the aircraft from wind turbine to radar ( $m^2$ )              |
| $\sigma_{w1}$     | The bi-static RCS of the wind turbine <sup>7</sup> from radar to aircraft ( $m^2$ ) |
| $\sigma_{w2}$     | The bi-static RCS of the wind turbine <sup>7</sup> from aircraft to radar ( $m^2$ ) |
| $F_{rw} = F_{wr}$ | Terrain induced attenuation factor between radar and wind turbine.                  |
| $F_{wa} = F_{aw}$ | Terrain induced attenuation factor between wind turbine and aircraft.               |
| $F_{ra} = F_{ar}$ | Terrain induced attenuation factor between radar and aircraft.                      |
| $D_{rw}$          | Distance radar to wind turbine (m)  |
| $D_{wa}$          | Distance wind turbine to aircraft (m)   |
| $D_{ra}$          | Distance radar to aircraft (m)  |
| $\lambda$         | Signal wavelength (m)   |

## C - 2 Further Processing

Whilst at its most basic the remainder of the radar can be modelled as a simple threshold detector by comparing  $P_{ref}$ , above, to a defined threshold ( $P_{thresh}$ ) for the radar under test this is a huge simplification for a modern radar system.

Other than to state that where possible as much of the radars internal processing should be taken into account it is not intended to go further within this document as data processing varies so widely from radar to radar and the relevant algorithms are often difficult to obtain or model. Some of the issues which may affect the probability of detection of aircraft reflection include the following items<sup>8</sup>:

- **Sliding window** - Most systems determine detection using a statistical M detections from N pulses algorithm;
- **Tracking Algorithms** - Plot-extracted systems will only provide plot information should a series of echoes over a number of scans pass certain tracking criteria.

<sup>8</sup> MTI-MTD filtering is not applicable in this case as the reflected signal will have the same Doppler characteristics as the direct aircraft echo.

---

## ANNEX - D Justification of the recommended SSR protection range

### D - 1 Introduction

The selection of the recommended SSR protection range is based on the assessment of 3 impacts that a single wind turbine could have on the SSR performance:

- Position detection and Mode A/Mode C code detection performance characteristics.
- Multiple target reports performance characteristic.
- Azimuth accuracy performance characteristic.

### D - 2 2D position detection and Mode A/Mode C code detection

As for PSR (see Annex - A), SSR is affected by a shadow region behind the wind turbine where the 2D position detection and the Mode A and Mode C code detection may be degraded. In the case of SSR the shadow length can be calculated.

The protection range has been calculated in such a way that the volume represented by region 1 (width, height and length) remains tolerably small.

SSR interrogations/responses can all be modelled as one-way communication links and probabilities of signal detection can be derived by from received signal power,  $P_r$ , and receiver sensitivity.  $P_r$  can be found by initially determining the power density,  $P$ , at a range of  $D$  from a transmitter radiating a signal with a power of  $P_t$ :

$$P = \frac{F.G_t.P_t}{4.\pi.D^2} \quad \text{Equation 19}$$

The radar's ability to collect this power and feed it to its receiver is a function of its antenna's effective area,  $A_e$ , and  $P_r$  is therefore given by the equation;

$$P_r = P.A_e \quad \text{Equation 20}$$

Replacing  $A_e$  with its actual value gives:

$$P_r = \frac{P.G_r.\lambda^2}{4.\pi} \quad \text{Equation 21}$$

Replacing  $P$  with the terms of Equation 19 gives:

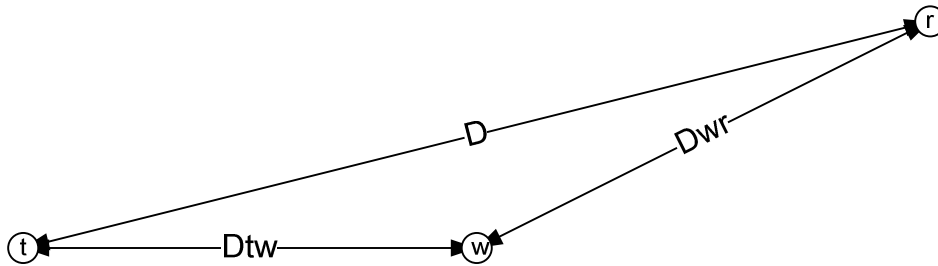
$$P_r = \frac{F.G_t.P_t.G_r.\lambda^2}{(4.\pi.D)^2} \quad \text{Equation 22}$$

when this signal is reflected off an object with bi-static radar cross section of  $\sigma$ , e.g. a wind turbine, rather than received directly, this equation can be modified to

$$P_{r\ ef} = \frac{\sigma.F_{tw}.F_{wr}.G_{tw}.P_t.G_{rw}.\lambda^2}{(4.\pi.)^3.D_{tw}^2.D_{wr}^2} \quad \text{Equation 23}$$

where the symbols have the following meanings

|           |  |
|-----------|--|
| $P_{ref}$ | The power of the reflected signal arriving at the receiver               |
| $P_t$     | Transmitted power  |
| $G_{tw}$  | Transmit antenna gain in the direction of the wind turbine               |
| $G_{wr}$  | Receive antenna gain in the direction of the wind turbine                |
| $\sigma$  | The bi-static RCS of the wind turbine <sup>7</sup> as in Figure 21.      |
| $F_{tw}$  | Terrain induced attenuation factor between transmitter and wind turbine. |
| $F_{wr}$  | Terrain induced attenuation factor between wind turbine and receiver.    |
| $D_{tw}$  | Distance transmitter to wind turbine                                     |
| $D_{wr}$  | Distance wind turbine to receiver  |
| $\lambda$ | Signal wavelength  |



**Figure 21: Direct and reflected signal paths**

By replacing the power received,  $P_{ref}$ , with the threshold of the receiving system,  $P_{thresh}$ , the range from the turbine for a given turbine/transmitter geometry where the reflected signal is likely to be detected is given by:

$$D_{wr} = \sqrt{\frac{\sigma \cdot F_{tw} \cdot F_{wr} \cdot G_{tw} \cdot G_{wr} \cdot P_t \cdot \lambda^2}{(4\pi)^3 \cdot D_{tw} \cdot P_{thresh}}} \quad \text{Equation 24}$$

For certain assessments the ratio of the power received via the direct path  $D$  has to be compared to the power received via the indirect path. Combining Equation 19 and Equation 23 yields:

$$\frac{P_{direct}}{P_{ref}} = \frac{F_{dir} \cdot G_t \cdot G_r \cdot 4\pi \cdot D_{tw}^2 \cdot D_{wr}^2}{\sigma \cdot G_{tw} \cdot G_{wr} \cdot D^2 \cdot F_{tw} \cdot F_{wr}} \quad \text{Equation 25}$$

By inverting Equation 25 we get the ratio between direct signal and reflected signal behind a turbine:

$$\frac{P_{ref}}{P_{direct}} = \frac{\sigma \cdot G_{tw} \cdot G_{wr} \cdot D^2 \cdot F_{tw} \cdot F_{wr}}{F_{dir} \cdot G_t \cdot G_r \cdot 4\pi \cdot D_{tw}^2 \cdot D_{wr}^2} \quad \text{Equation 26}$$

For point "A", directly behind the turbine, we can use the following relationships:

$$G_{tw} = G_t$$

$$G_{wr} = G_r$$

$$D = D_{tw} + D_{wr}$$

$$F_{dir} = F_{tw} \cdot F_{wr}$$

$$\sigma = \frac{4 \cdot \pi \cdot L^2 \cdot S^2}{\lambda^2}$$

$$L^2 = \frac{\lambda}{\frac{1}{D_{tw}} + \frac{1}{D_{wr}}}$$

Where L is the dimension of the 1<sup>st</sup> Fresnel zone and S is the diameter of the mast, this gives us:

$$\frac{P_{ref}}{P_{direct}} = \frac{S^2 \cdot D}{D_{tw} \cdot D_{wr} \cdot \lambda} \quad \text{Equation 27}$$

Using the relationship between field strength and power loss, PL, we get:

$$PL = \left(1 - \sqrt{\frac{P_{ref}}{P_{direct}}}\right)^2 = \left(1 - S \cdot \sqrt{\frac{D}{D_{tw} \cdot D_{wr} \cdot \lambda}}\right)^2 \quad \text{Equation 28}$$

Which can be rearranged to give:

$$D_{wr} = \frac{D_{tw}}{\left(\frac{D_{tw} \cdot \lambda}{S^2} \cdot (1 - \sqrt{PL})^2 - 1\right)} \quad \text{Equation 29}$$

Which is the length of the shadow region for a given acceptable 1-way power loss PL.

Assuming that a 3 dB power loss is tolerable in the case of an SSR and a mast diameter of 6 m and taking into account  $D_{tw} \geq 16$  km, the maximum length of the shadow region is equal to 1600 m.

At 1600 m behind the wind turbine the shadow height (see Annex A - 2) is equal to 310 m assuming a wind turbine height of 200 m (nacelle height + half rotor blade diameter) and that the wind turbine altitude is 50 m higher than the SSR.

Using Equation 4 the width of the shadow region can be calculated and is equal to 45 m.

Under these conditions and assumptions the volume of the SSR shadow region behind a wind turbine (l 1600 m x w 45 m x h 310 m) is sufficiently small to be operationally tolerable.

The above assessment has been performed for a single wind turbine. Would there be multiple wind turbines located in a radar beam-width, the resulting shadow zone would be larger. Nevertheless it is believed that the 16 km limit is a valid figure for the border between SSR zone 2 (detailed assessment) and SSR zone 4 (no assessment).

---

### D - 3 Multiple target reports

Here the calculation is based on the conditions to get a reply from a transponder when the interrogation has been reflected onto a wind turbine.

Because of the ISLS implementation, the transponder will be insensitive during a 35  $\mu$ s (see § 3.1.1.7.4 [RD 2]) period after the reception of a radar interrogation through radar sidelobes. Therefore any aircraft/transponder located closer than 5250 m (half of the distance corresponding to 35  $\mu$ s) will not reply to reflected interrogations because in this case the path difference between the direct (through sidelobes) and the reflected signal will always be smaller than 35  $\mu$ s.

When the aircraft transponder is located further than 5250 m from the wind turbine, the minimum power received by the transponder from a reflected interrogation can be calculated (using Equation 23) and can be compared with the minimum transponder receiver threshold (smaller specified value -77 dBm § 3.1.1.7.5 [RD 2]). Therefore the minimum distance between the SSR and the wind turbine can be calculated as follows:

$$D_{tw} = \sqrt{\frac{\sigma \cdot F_{tw} \cdot F_{wr} \cdot G_{tw} \cdot G_{wr} \cdot P_t \cdot \lambda^2}{(4 \cdot \pi)^3 \cdot D_{wr}^2 \cdot P_{thresh}}} \quad \text{Equation 30}$$

$$P_{thresh} = -77 \text{ dBm} = 10^{-10.7} \text{ W}$$

$$P_t = 2 \text{ kW} = 2000 \text{ W}$$

$$F_{tw} = F_{wr} = 1$$

$$\sigma = 35 \text{ dBm}^2 = 10^{3.5} \text{ m}^2$$

$$G_{tw} = 27 \text{ dB} = 10^{2.7}$$

$$G_{wr} = 1$$

$$D_{wr} = 5250 \text{ m}$$

$$\lambda = 0.2913 \text{ m (corresponding to 1030 Mhz)}$$

It gives:

$$D_{tw} = 15698 \text{ m}$$

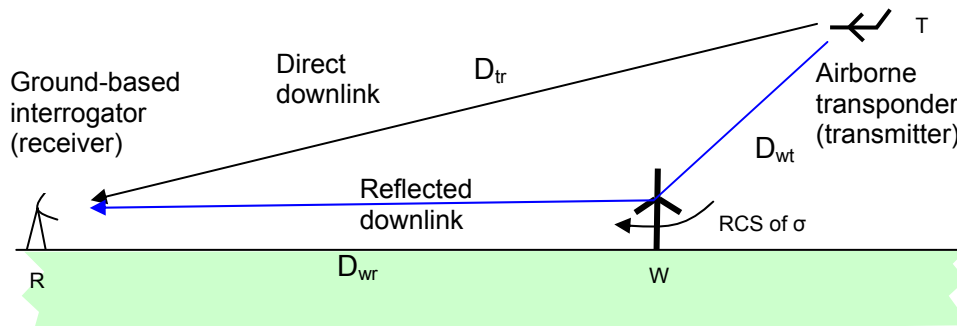
Therefore when the wind turbine is 16 km away from the SSR if the aircraft/transponder is located closer than 5250 m from the wind turbine the transponder will not reply to reflected interrogations because of ISLS implementation and when further than 5250 m the power of the reflected interrogation will be below the transponder receiver threshold and the transponder will not reply either.

It must be noted that the rationale above is only valid for Mode A/C operations.

### D - 4 Azimuth accuracy

Here the calculation is based on the azimuth error due to a wind turbine for aircraft located behind the wind turbine.

As explained in paragraph 4.4.11, azimuth error may happen when there is a small path difference (less than  $0.25 \mu\text{s} = 75 \text{ m}$ ) between the direct and the reflected signals as illustrated on Figure 22 below.



**Figure 22: SSR downlink reflection**

If the above criterion on path difference is met, this will have an impact on the azimuth measurement if the ratio  $C/I$  between the direct signal ( $C$  – Carriage) and the reflected signal ( $I$  – Interference) is smaller than a given threshold.

The  $C/I$  ratio can be calculated as follows assuming that:

- The propagation losses to the wind turbine and to the aircraft from the SSR ground system are the same;
- The propagation losses between the transponder and the wind turbine and the transponder and the SSR ground system are the same;
- The transponder gain in the direction of the wind turbine is the same in the direction of the SSR ground system;
- The SSR ground system receive gain is the same in the direction of the wind turbine as in the direction of the transponder.

If the above assumptions are met then:

$$\frac{C}{I} = \frac{D_{tw}^2 D_{wr}^2}{D_{tr}^2} \frac{4\pi}{\sigma} \quad \text{Equation 31}$$

Where  $\sigma$  is the wind turbine bi-static RCS<sup>7</sup> as in Figure 22.

As  $D_{tw} \leq D_{tr}$ , it can be derived that:

$$\frac{C}{I} \leq \frac{4\pi}{\sigma} \cdot D_{wr}^2 \quad \text{Equation 32}$$

Therefore, taking into account that a  $C/I$  ratio of 50 dB is largely sufficient to ensure a good discrimination between the direct signal and the reflected signal, one can derive the minimum  $D_{wr}$  for a given (maximum) bi-static wind turbine RCS (e.g.  $\sigma = 35 \text{ dBm}^2$ ).

$$D_{wr} = 5016 \text{ m}$$

---

Consequently, when the wind turbine is more than 16 km away from the SSR, the impact on azimuth accuracy is tolerable irrespective of the path difference between the direct and the reflected signal.

The above assessment has been performed for a single wind turbine. It should be noted that would there be multiple wind turbines located in a radar beam-width and at a larger distance than 5 km, the resulting SSR azimuth error could be significant.

---

## ANNEX - E Wind energy project description pro-forma

The pro-forma below is based on a form currently in used; it can be adapted in accordance with national regulations and practice (see yellow shaded cell).

|  |  |
|--|--|
| Wind Farm Name   |  |
|  |  |
| Also known as:   |  |
|  |  |
| Developers reference   |  |
| Application identification No.   |  |
|  |  |
| Related/previous applications<br>(at or near this site):<br>Provide reference names or numbers |  |

|                              |  |
|------------------------------|--|
| <b>Developer Information</b> |  |
| <b>Company name:</b>         |  |
|                              |  |
| <b>Address:</b>              |  |
|                              |  |
| <b>Contact:</b>              |  |
|                              |  |
| <b>Telephone:</b>            |  |
|                              |  |
| <b>Facsimile:</b>            |  |
|                              |  |
| <b>e-mail:</b>               |  |



## Relevant Wind Turbine Details

|   |           |                    |
|---|-----------|--------------------|
| Wind turbine manufacturer:                    |           |                    |
| Wind turbine model:                           |           |                    |
| Wind farm generation capacity (MW)            |           | Number of turbines |
| Blade manufacturer                            |           |                    |
| Number of blades                              |           |                    |
| Rotor diameter                                |           | Metres             |
| Rotation speed (or range)                     |           | Rpm                |
| Blade material including lightning conductors |           |                    |
| Wind turbine hub height                       |           | Metres             |
| Tower design (* delete as required)           | * Tubular | * Lattice          |
| Tower base diameter/dimensions                |           | Metres             |
| Tower top diameter/dimensions                 |           | Metres             |

### Comments

Are there any details or uncertainties that may be helpful to add?

## Turbine Locations

Please provide as much information as you can. The base position and tower height above sea level of every wind turbine if available, the site boundary if not.

Please number the turbines or boundary points on the map, to correlate with the information provided below.

**Copy this page as necessary** to account for all turbines or boundary points

Wind farm  
Name & Address:

|                       |         |   |  |         |
|-----------------------|---------|---|--|---------|
| <b>Turbine no.</b>    |         | <b>Height</b> above a known reference (m) of tower base |  |         |
|                       | Degrees | Minutes   |  | Seconds |
| <b>Latitude</b>       |         |   |  |         |
| <b>Longitude</b>      |         |   |  |         |
| <b>Turbine no.</b>    |         | <b>Height</b> above a known reference (m) of tower base |  |         |
|                       | Degrees | Minutes   |  | Seconds |
| <b>Latitude</b>       |         |   |  |         |
| <b>Longitude</b>      |         |   |  |         |
| <b>Turbine no.</b>    |         | <b>Height</b> above a known reference (m) of tower base |  |         |
| <b>Grid Reference</b> |         | 100 km square letter(s) identifier                      |  |         |
| <b>Latitude</b>       |         |   |  |         |
| <b>Longitude</b>      |         |   |  |         |
| <b>Turbine no.</b>    |         | <b>Height</b> above a known reference (m) of tower base |  |         |
|                       | Degrees | Minutes   |  | Seconds |
| <b>Latitude</b>       |         |   |  |         |
| <b>Longitude</b>      |         |   |  |         |





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