FFI RAPPORT

WIND TURBINES AND ELECTROMAGNETIC SYSTEMS (WTES) - Software documentation

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d)	d)
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8) ABSTRACT

This report contains a description of the software developed by the FFI-project 1013 “Effekt av vindkraftutbygging på radiosamband og radar (VINDKRAFT)” (The effect of windmill development on telecommunication and radar).

The software will be connected to MARIA, a chart handling system developed by Teleplan in cooperation with the Norwegian Defence, and WIMP (Windfarm Impact on electromagnetic systems) developed by Teleplan on contract by the FFI project 1013.

The MARIA – WIMP combination is only a tool to enter objects used in the analysis and to present results from the analyses. The calculation of the actual impact of the windfarms is done in the WTES (Wind Turbine and Electromagnetic Systems) software developed by FFI.

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CONTENTS

WIND TURBINES AND ELECTROMAGNETIC SYSTEMS (WTES) - Software documentation

1 INTRODUCTION

This report contains a description of the WTES software developed by the FFI-project 1013 “Effekt av vindkraftutbygging på radiosamband og radar (VINDKRAFT)” (The effect of windmill development on telecommunication and radar).

The software will be connected to MARIA, a chart handling system developed by Teleplan in cooperation with the Norwegian Defence, and WIMP (Windfarm Impact on electromagnetic systems)(1) developed by Teleplan on contract for the FFI project 1013.

The MARIA – WIMP combination is only a tool to enter objects used in the analysis and to present results from the analyses. The calculation of the actual impact of the windfarms is done in the WTES (Wind Turbine and Electromagnetic Systems) software developed by FFI. The first four chapters will give an overview of the program, chapter 5 describes how to install the proagram and chapter 6-11 is a user manual for the program. Chapter 12 summarizes the report and appendix A-L gives the theoretical background for the calculations.

2 WHAT IS WTES

WTES is an abbreviation for Wind Turbines (WT) and Electromagnetic Systems (ES). It has been developed by Forsvarets forskningsinstitutt (FFI) (Norwegian Defence Research Establishment) to predict the influence of windturbines and windfarms (WF) on radar, radio links and passive systems.

The knowledge of WT on ES is gradually increased through international scientific work. The development of WTES is based on the available knowledge national and international. To help each user to judge on the models quality a description of the technical background is included.

The WTES is divided into five modules covering the main electromagnetic systems: Radar, Secondary Surveillance Radar (SSR), Radio Links, Passive Systems and High Frequency Systems (HF). This report describes all modules.

3 OVERALL DESCRIPTION

WIMP (1) is used as a tool to enter objects used in the analysis and to present results from the analyses. The project entered in WIMP will be stored in an xml-file. WTES reads the actual xml file(s) and executes the selected calculations and analysis. To visualize the results of these calculations and analysis, WTES generates an xml file and accompanying bitmap file, as described later in this report (chapter 4).

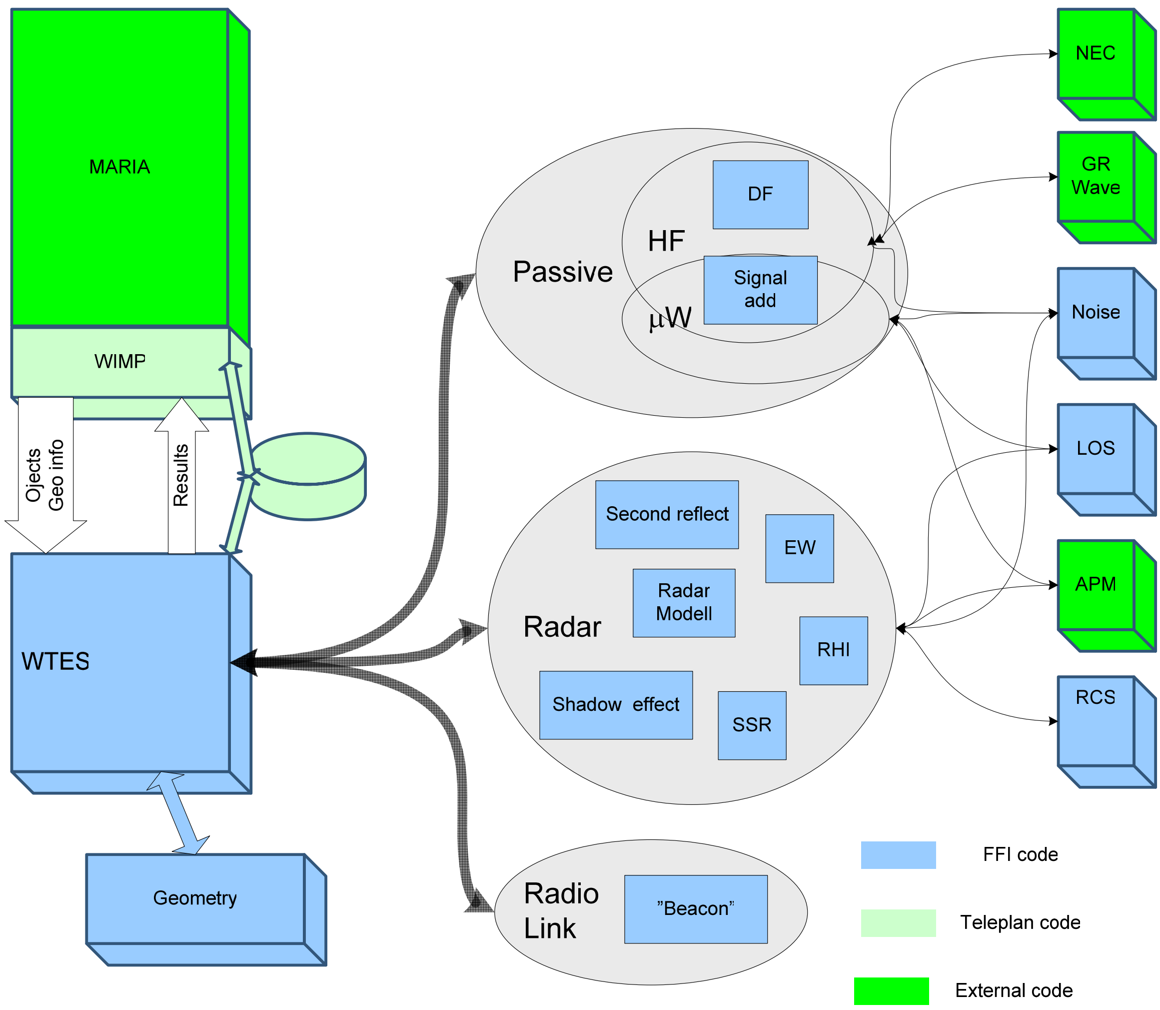


Figure 3.1 Overview of the different programs involved.

The WTES includes all the blocks in the middle and right of Figure 3.1. The calculation opportunities are shown in Figure 3.2.

The WTES is implemented in LabVIEW 8.2. The code is based on event handling and event queuing. The executable code will be independent of having LabVIEW installed at your computer (see chapter 5).

The Graphical User Interface is organized with pull-down menus and push buttons. The results are shown in WTES, or written to files for presentation in WIMP.

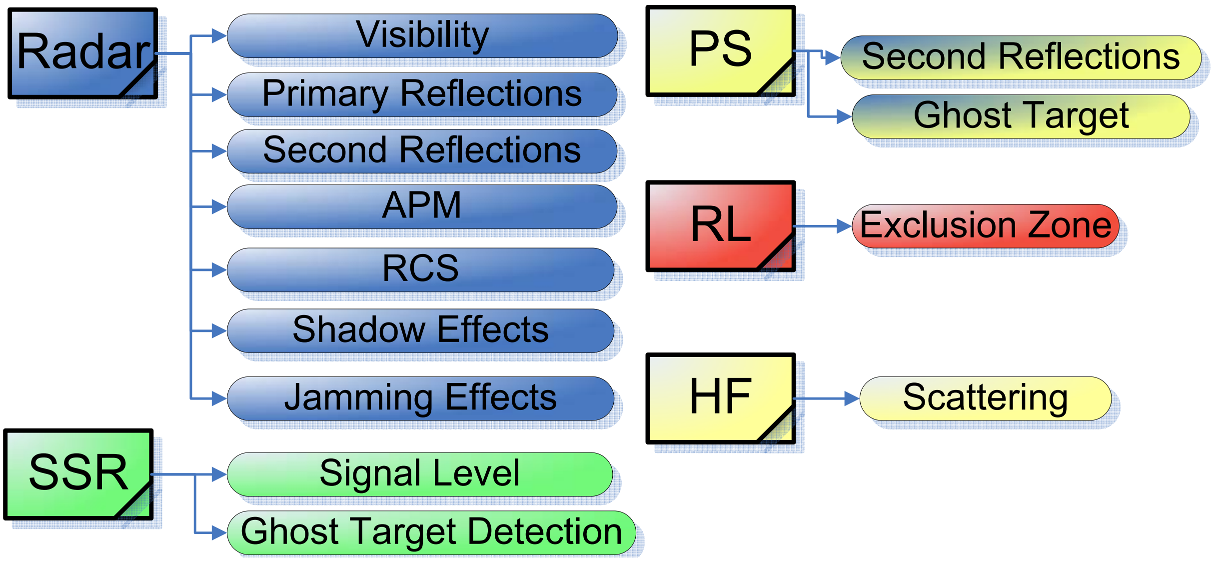


Figure 3.2 The calculation opportunities for the different modules.

4 EXCHANGE OF DATA BETWEEN WTES AND WIMP

The communication is done by use of xml and bitmap files, as shown in Figure 4.1.

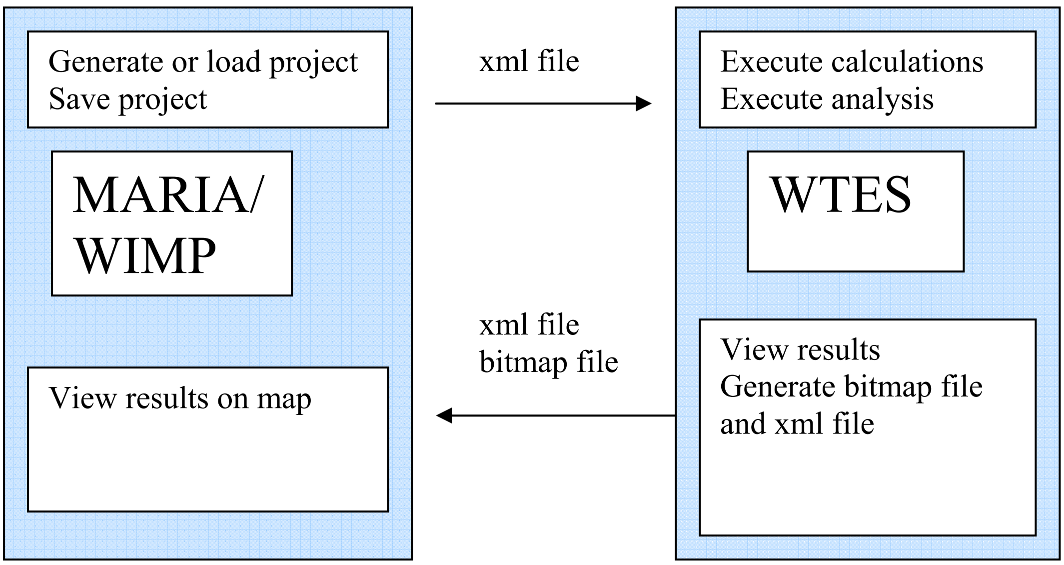


Figure 4.1 Communication between WIMP and WTES

4.1 Reading WIMP data

WTES reads data from xml file(s) stored in WIMP. The xml file contains objects and attributes, and the format of the xml file is given in (1).

The data are stored in global LabVIEW variables, containing clusters of data. The data are used in calculations, analysis and presented to the user.

4.2 Writing WIMP data

WTES can make changes to existing projects and save the updated project. The object data including their attributes will be written to an xml file according to the format described in (1).

5 INSTALLING WTES

The DVD contains DTED Map, Run LabVIEW_8.2_Runtime_Engine.exe and WTES Installer.exe.

1) Copy the DTED Map folder to your computer (this path must be set in WTES main settings, see section 6.1 and Figure 6.4)
2) Run LabVIEW_8.2_Runtime_Engine.exe
3) Run WTES Installer.exe

6 USER MANUAL

Starting the WTES program gives the main window shown in Figure 6.1.

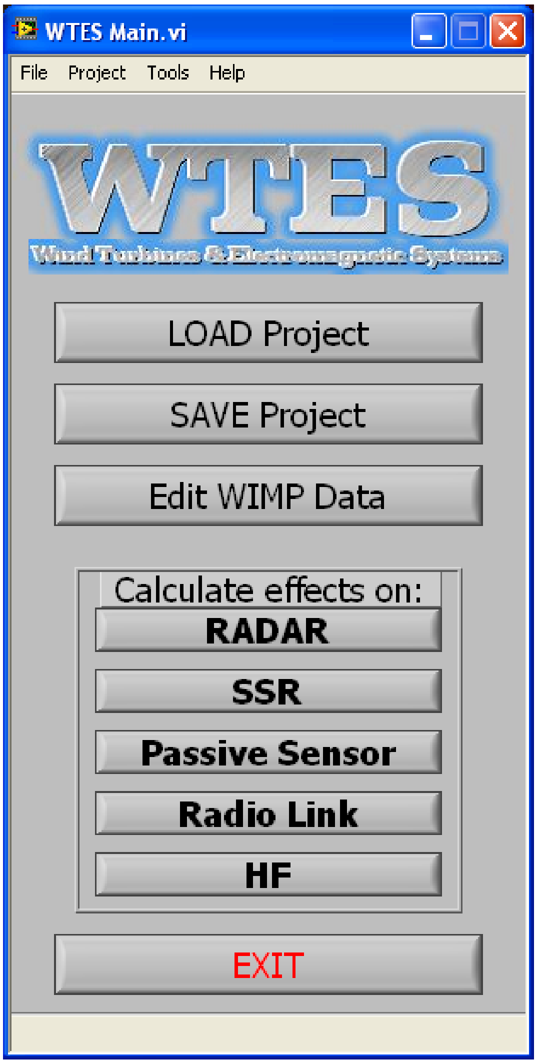
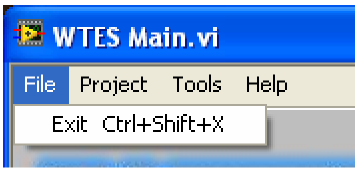


Figure 6.1 Main window

6.1 Main Pull-down Menu



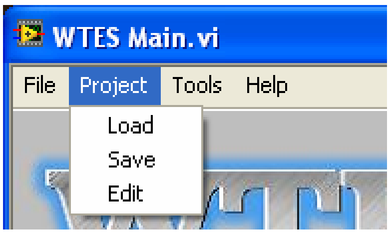
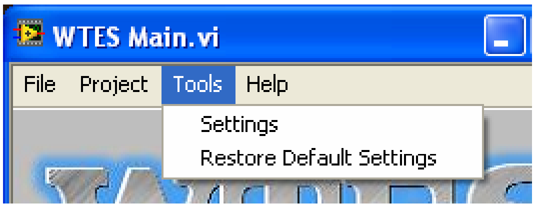


Figure 6.2 Main Pull-down Menu – File and Project

Figure 6.2 shows the pull-down menu for File and Project. These options are also found as separate buttons on the main window (see Figure 6.1).

- File
    - Exit – close the whole program (or use the EXIT button)

- Project
    - Load – loads a project (see 6.2.1)
    - Save – saves a project (see 6.2.2)
    - Edit – Edit WIMP Data (see 6.2.3)



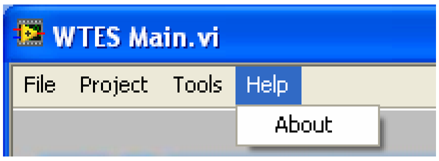


Figure 6.3 Main Pull-down Menu – Tools and Help

Figure 6.3 shows the pull-down menu for Tools and Help

- Tools
    - Settings (see below)
    - Restore Default Settings – restores all default settings
- Help
    - About (see below)

Settings:

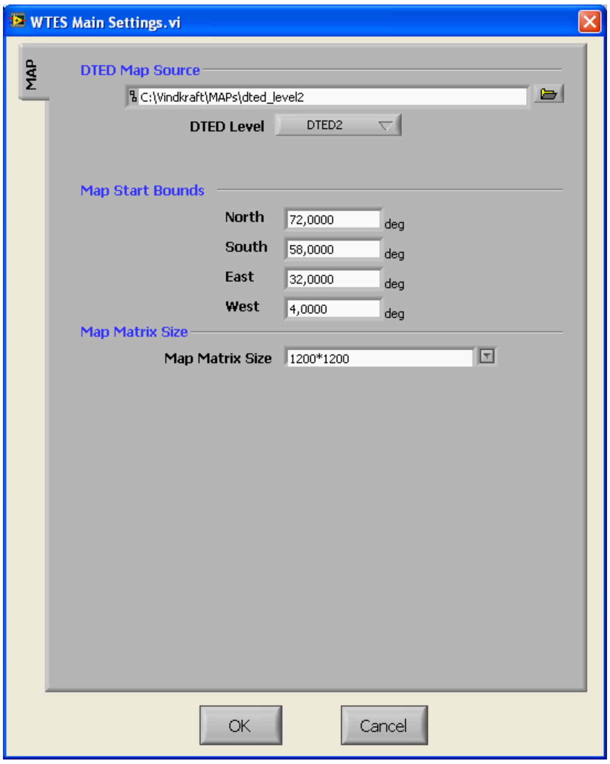


Figure 6.4 Settings in Main Menu (Default values).

The possible settings are, like seen in Figure 6.4:

- DTED Map Source
  - Tells WTES where the DTED map data are stored
- DTED Level
  - Gives the resolution of the map, DTED2 gives the best resolution
- Map Start Bound
  - The coordinates of the map (WGS84) (Default values gives Norway).
- Map Matrix Size
  - The size of the map shown in WTES (in pixels)

Help:

Figure 6.5 About WTES.

6.2 Project handling

The project handling may be done by the main pull-down menu or the buttons on the main window.

6.2.1 Load

Loads the xml-file from WIMP, the format of this file is given in (1). The objects attributes may be changed in the Edit WIMP Data.

6.2.2 Save

Saves an xml-file from WTES, the format of this file is given in (1). If two or more projects are loaded into WTES, they are stored together in one xml-file by SAVE.

6.2.3 Edit WIMP Data

A new window opens and shows the WIMP data in tables. Select the actual object from the list by double click the name. Another window opens showing the parameters for the chosen object as shown in Figure 6.6. Change the desired parameter(s) and push OK. The updated data can be saved by pushing the SAVE Project button (Figure 6.1).

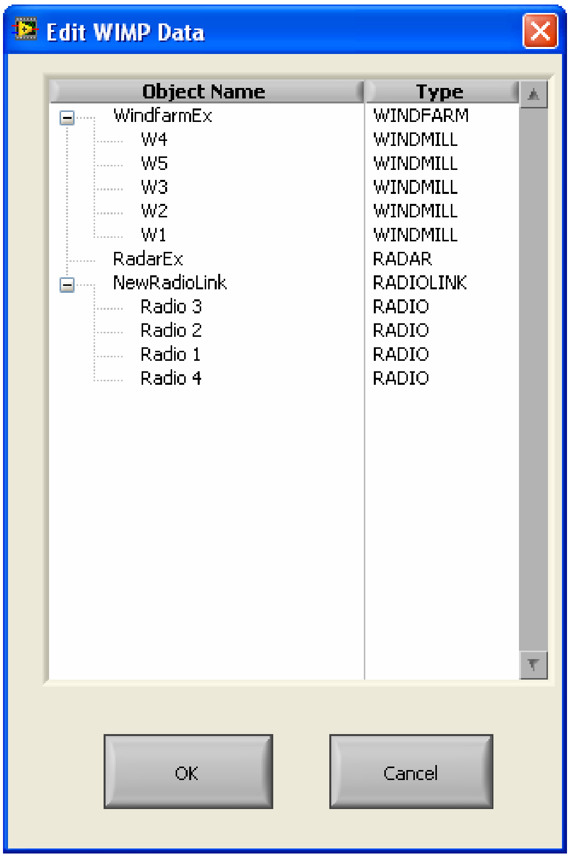


Figure 6.6 Show, add, edit and save WIMP data.

6.3 Select Electromagnetic System

After locating the map (Figure 6.4) and loading a project (section 6.2.1) select the electromagnetic system you want to analyze. The selection is done by pushing the corresponding button in the main menu (Figure 6.1). Radar is described in section 7, SSR in section 8, Passive sensors in section 9, Radio Link in section 10 and HF in section 11.

If no map is shown in the view of the selected electromagnetic system, check that the link to your map data is correct (see Figure 6.4).

The windows for the different electromagnetic system are rather similar, except for the calculation opportunities. They all have a pull-down menu as described in the subsections.

6.3.1 Pull-down Menu

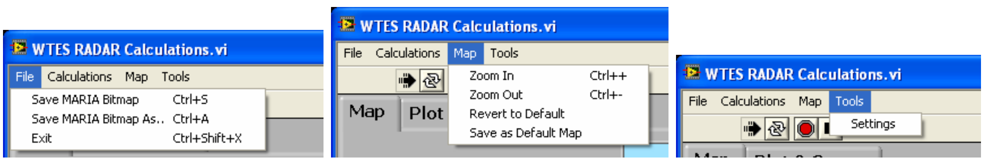


Figure 6.7 Pull-down menu for the different electromagnetic systems. Calculation menu will vary according to selected system.

Figure 6.7 shows the pull-down menu for all the electromagnetic systems

- File
    - Save MARIA Bitmap (see section 6.4)
    - Save MARIA Bitmap As .. (see section 6.4)
    - Exit – exit this electromagnetic system and return to the main window.
- Calculations
    - See the description of the different electromagnetic systems (section 7-11).
- Map
    - Zoom In – zoom the map in
    - Zoom Out - zoom the map out
    - Revert to Default – revert to the latest saved map settings
    - Save as Default Map – save current settings as default map settings (using the Restore Default Settings (6.1) will overwrite these settings)
- Tools
    - Settings – described for the different electromagnetic systems (section 7-11).

6.3.2 Mouse Menu

The mouse menu is different in the Map area and the Plot & Curves area.

In the Map area:
Right clicking the mouse gives a menu

- Centre Map
- Zoom In
- Zoom Out

In the Plot & Curves area:
Moving the mouse onto the bitmap shows a short description (tip strip) for the bitmap.

Right clicking the mouse gives a menu

- Copy Data
- Description and Tip ..
- Smooth Updates

By selecting the Description and Tip .. you see a description for the bitmap together with the short description (Tip). You may copy the bitmap window by selecting Copy Data and choose whether you want Smooth Updates or not.

6.3.3 Radars and Windmills

If your project has more than one radar and/or wind farm you have to select which one to do the calculations on. This is done by selecting the tab “Plots & Curves”, and then select the desired radar/windmill as shown in Figure 6.8.

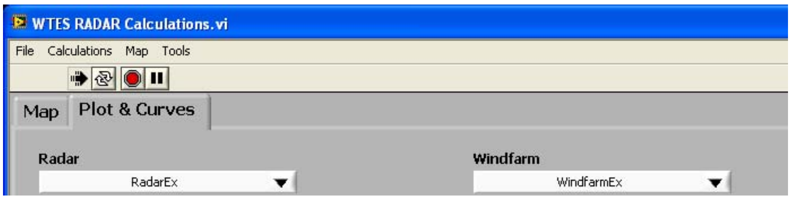


Figure 6.8   Select the radar/windmill to do calculations on.

6.4 Saving WTES bitmaps

The bitmaps results form the different calculations in WTES appears in the Bitmaps list as Current (see Figure 6.9). You may save the bitmap to be able to view it in the chart display on WIMP/Maria or to recall it in the WTES later for instance to compare to other bitmaps. To save a bitmap, select the “File” option in the main pull-down menu (section 6.1). The program then generates two files with the same name but different extension; an xml file describing the position, size and orientation and the bitmap file. The format of the file is described in (1). Default file name and file location may be set in Settings for the different calculations.

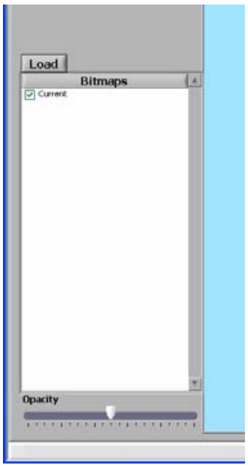


Figure 6.9   Saving bitmaps in WTES. Extract of Figure 7.3 .

To load a stored bitmap, push the Load button (see Figure 6.10). Many bitmaps can be in the list at the same time and you may choose which one to be shown in the map by marking the actual bitmaps.

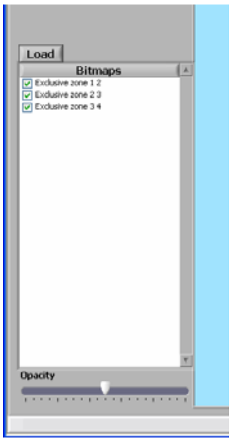


Figure 6.10   Loading bitmaps in WTES. Extract of Figure 10.2.

7   RADAR

To analyze the effects on radar systems, push the button for RADAR. The window shown in Figure 7.1 opens on the screen.

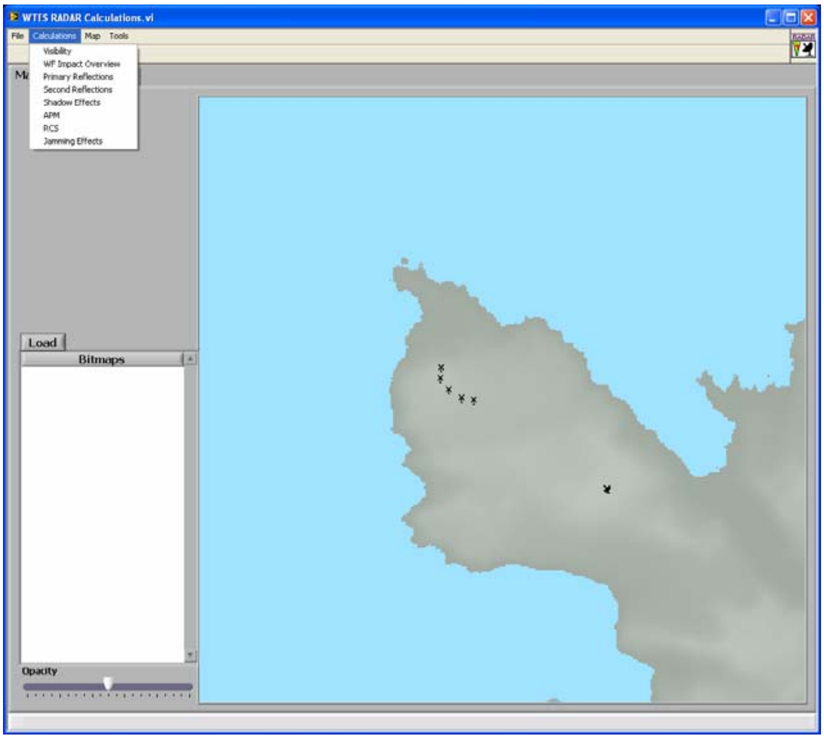


Figure 7.1   The menu window for RADAR calculations and analysis. The different calculation options are shown in the pull-down menu.

In the pull-down menu at the top of the window you select what **calculations** to perform. The different options are described in the following sections. There are eight possible calculations for the radar system. You may start by calculating the Visibility to find whether the windmills are in the line-of-sight from the radar or not. Be aware of the limitation of the calculation as described in A.1. If visible, use the WF Impact overview to get an overview of the situation. Use the other calculation option to evaluate the situation and demonstrate the different influences to the radar.

7.1 Radar Settings

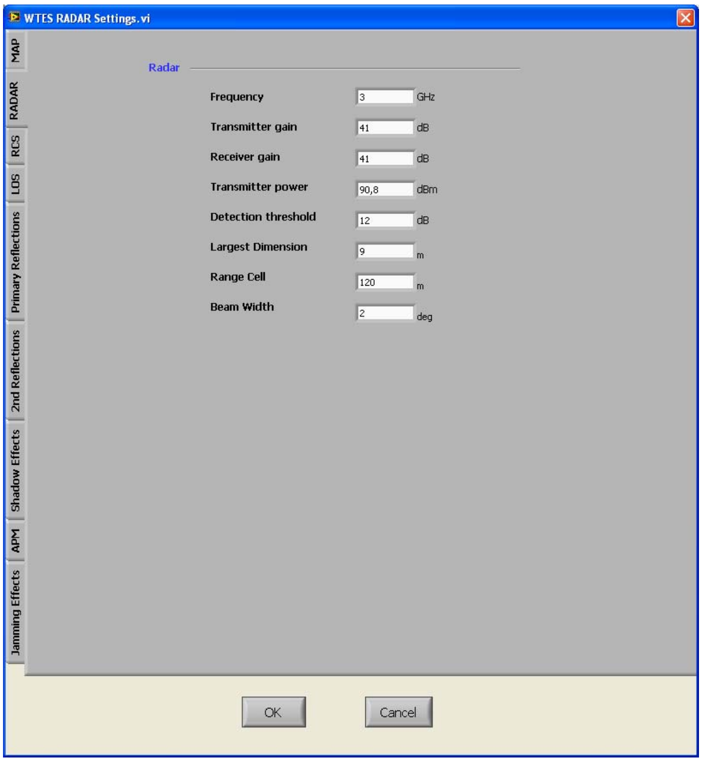


Figure 7.2 Settings for the Radar (Default settings).

The possible settings are, like seen in Figure 7.2:

- Frequency (GHz)
- Transmitter Gain (dB)
- Receiver Gain (dB)
- Transmitter Power (dBm)
- Detection Threshold (dBm)
- Largest Dimension of radar antenna (m)
- Range Cell (m)
- Beam Width (deg)

These settings are used for all the radar calculations. In addition other parameters are set in local settings for the different calculations (according to the different tabs on the settings left side, see Figure 7.2).

7.2 Visibility

Selecting the Visibility option generates a colored bitmap showing the results of the LOS calculations. An example of a Visibility calculation is shown in Figure 7.3, and the calculations are described in section A.1.

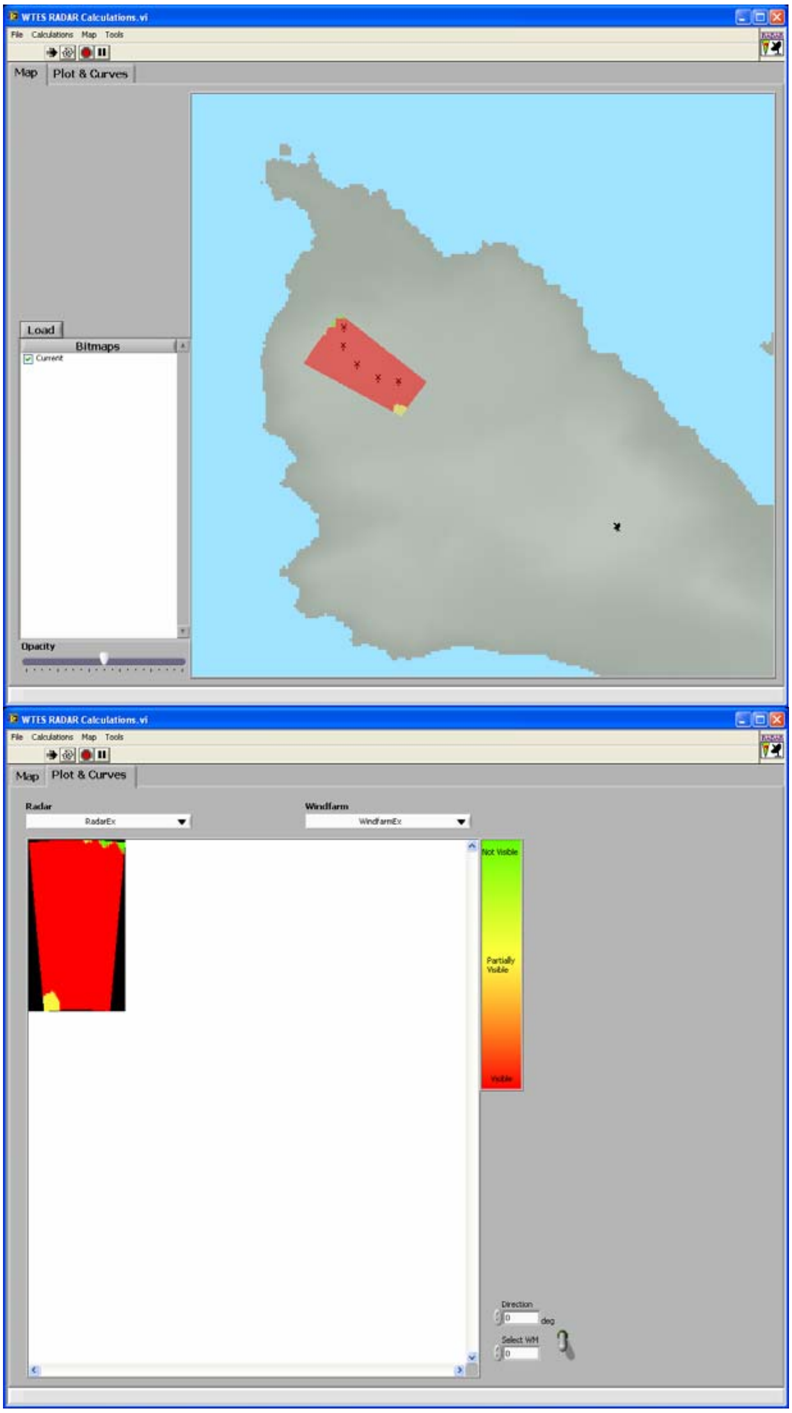


Figure 7.3 Example of Visibility Calculation

The calculations prepare a bitmap file, using different colors to indicate whether the various wind turbines are not visible (green), partly visible (yellow) or completely visible (red). These are solely based on Line-of-sight calculations according to terrain, but not according to signal deflection, as described in chapter A.1.

7.2.1 Settings

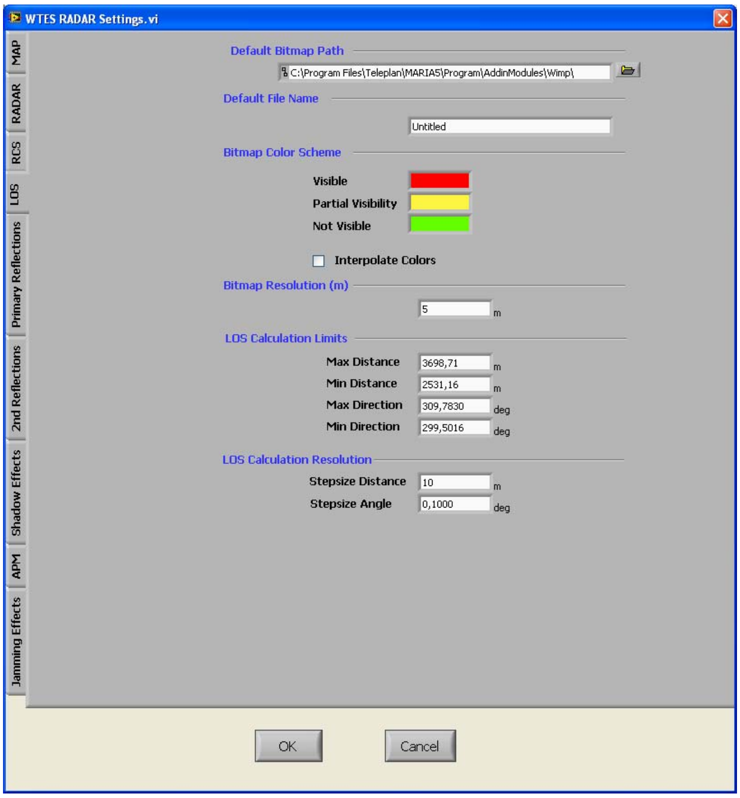
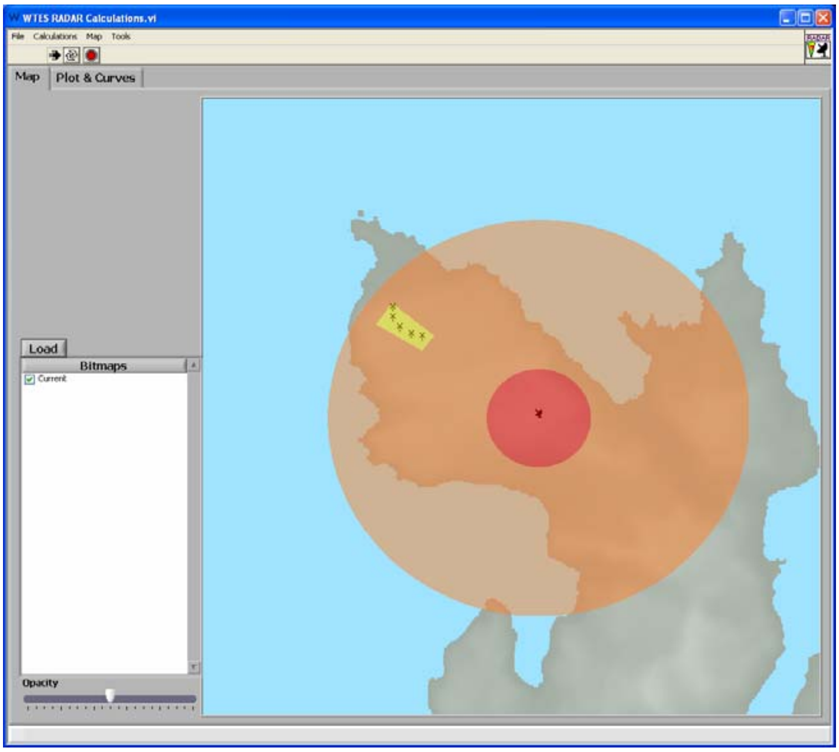


Figure 7.4 Settings for the calculations of visibility (Default settings).

The possible settings are, like seen in Figure 7.4:

- Bitmap resolution
  - The resolution of the plot.
- LOS Calculation Limits
  - The limits are automatically calculated from the wind farm area, as described in chapter A.1. The limits may be changed manually.
- LOS Calculation Resolution
  - The resolution of the calculations, as described in chapter A.1.

7.3 Windfarm Impact Overview



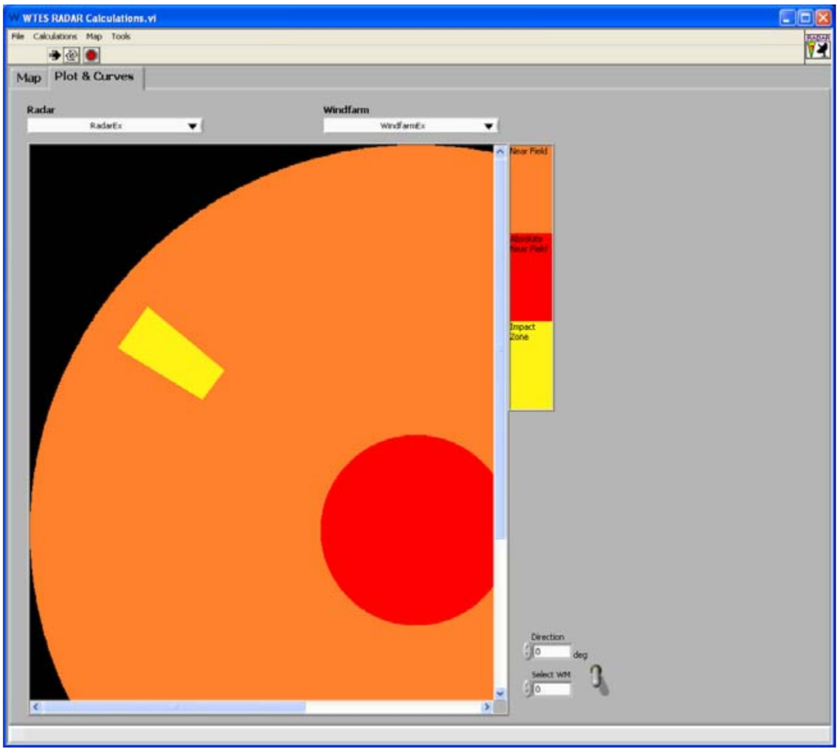


Figure 7.5 Example of WF Impact Overview diplay showing range and azimuth extent of severely affected area (CFAR/C-map and false target) plus the two range rings (absolute range limit and minimum range of calculation validity)

This calculation assumes that the wind park is within line-of-sight of the radar (see section 7.2).

The WF Impact Overview module calculates the area of severe radar influence by the wind park. The module produces a range and azimuth limited sector around the windmill park where false targets may appear due to false detections from the rotors or double reflections off the wind park and real targets, and where targets may be lost due to deteriorated CFAR or clutter map processing performance. The range rings show whether or not the specific situation being analysed is within the validity area of the module. Within the innermost range ring the calculations loose all validity, and between the innermost and outermost range ring additional evaluations such as on-site experiments should be performed.

Calculations and assumptions used for this module are shown in chapter B.

7.3.1 Settings

The radar settings are shown in Figure 7.2, an extract is shown in Figure 7.6.

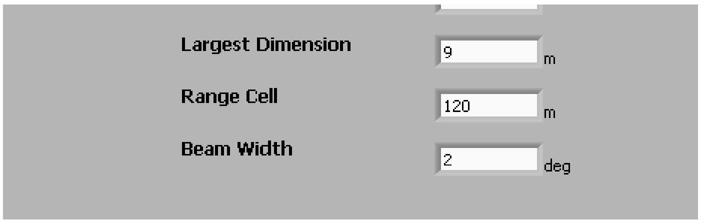


Figure 7.6 Extract of radar settings (Figure 7.2) actual for the WF Impact Overview (Default values).

The possible parameter settings are, as seen in Figure 7.6:

- Largest Dimension
- Range Cell
- Bean Width

Based on the parameters the Impact Zone is given by:

- Range affected area = wind park range extent + **Range Cell** in both directions
    - Should reflect actual radar clutter map or CFAR range extent
- Azimuth affected area = wind park azimuth extent + **1 antenna beam width** in both directions
    - Should reflect actual radar clutter map or CFAR azimuth extent

The Absolute Near Field is, according to the discussion in B:

- Inner range ring radius = 1 km.

The Near Field is given by:

- Outer range ring radius = $5D^2/\lambda$ where D is the Largest dimension and λ is the wavelength.

7.4 Primary reflections

Selecting the Primary Reflections option generates a colored bitmap showing the results of the Primary Reflections calculations. An example of a Primary Reflections calculation is shown in Figure 7.7. The theory is described in section C.

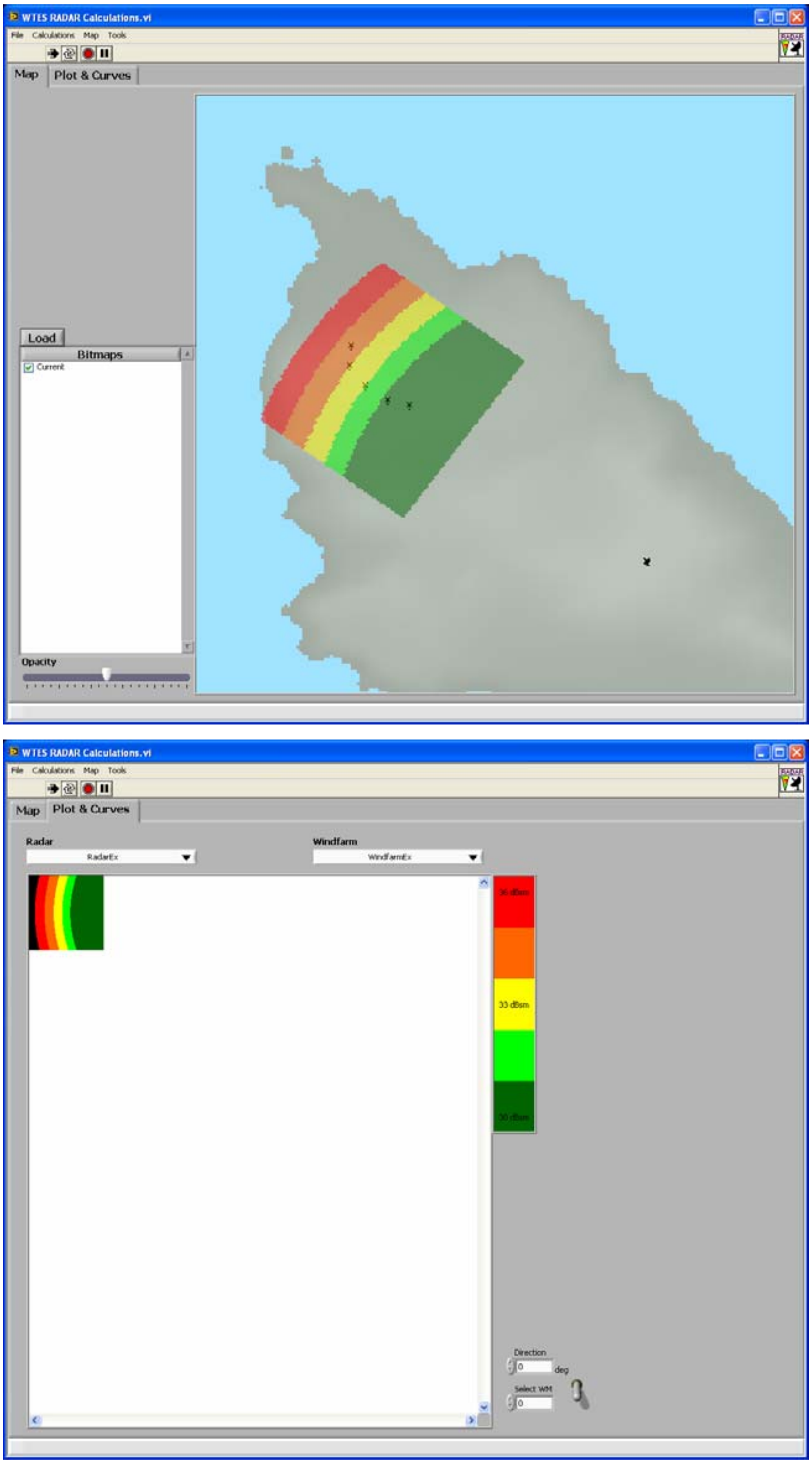


Figure 7.7 Example of a Primary Reflections calculation. Selected mode is Windmill RCS.

It is possible to choose between two different modes for the calculations:

1) Windmill RCS:

Calculates the RCS required for the windmill to be detected by the radar at a given distance (assuming free line of sight between the radar and the windmill). See Figure 7.7.

2) Minimum Distance:

Calculates the minimum required distance between the radar and a windmill with given RCS (see settings in Figure 7.9) in order for the radar not to detect the windmill (assuming free line of sight between the radar and the windmill). Areas where the radar can detect the windmill are shown in red colour, while areas where the radar cannot detect the windmill are shown in green. See Figure 7.8.

Figure 7.8 Example of a Primary Reflections calculation. Selected mode is Minimum Distance.

7.4.1 Settings

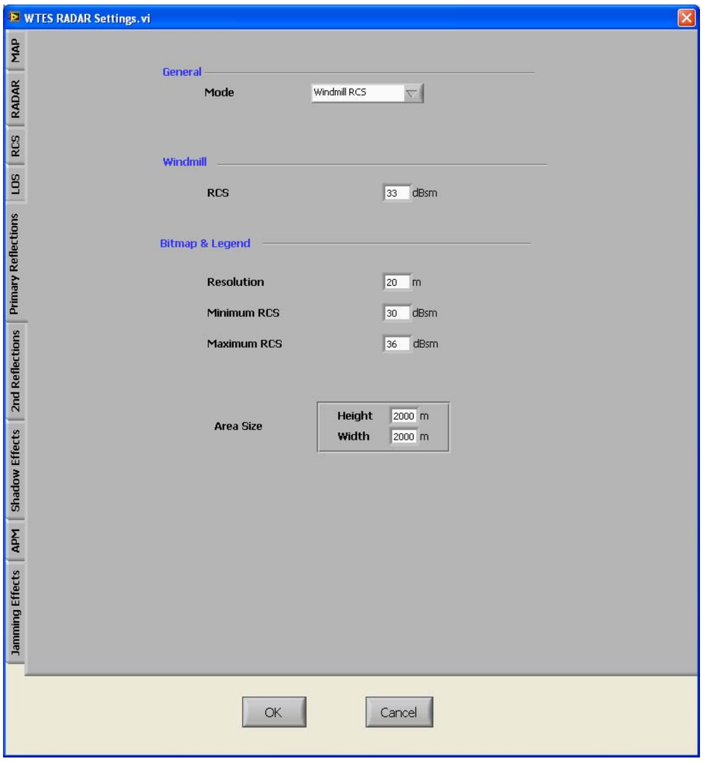


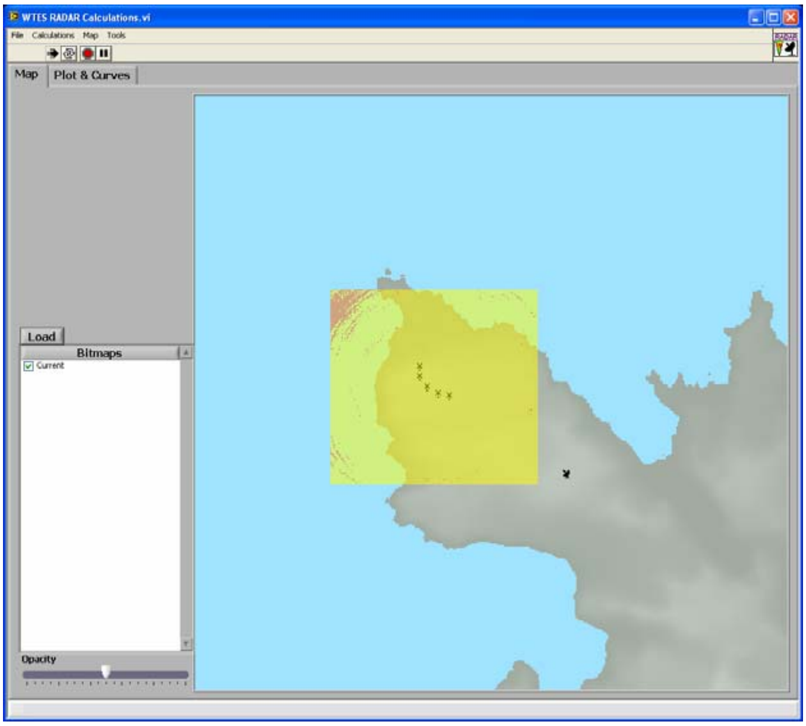
Figure 7.9 Settings for the Primary Reflections calculations (Default values).

The following settings are specific to the Primary Reflections calculations (see also Figure 7.2):

- Mode (See section 7.4):
  - Windmill RCS
  - Minimum Distance
- RCS
  - Windmill radar cross section (dBsm). Used only for the “Minimum Distance” mode. Values may be found in the RCS calculations (see section 7.8).
- Resolution
  - Resolution of the bitmap grid (m).
- Minimum RCS
  - Minimum RCS displayed in the bitmap (dBsm).
- Maximum RCS
  - Maximum RCS displayed in the bitmap (dBsm).
- Area Size
  - Height and width of the bitmap/targeted area (m).

7.5 Second Reflection

Selecting the Second Reflection option generates a colored bitmap showing the results of the second reflection calculations. An example of a Second Reflection calculation is shown in Figure 7.10, and the calculations are described in section D.



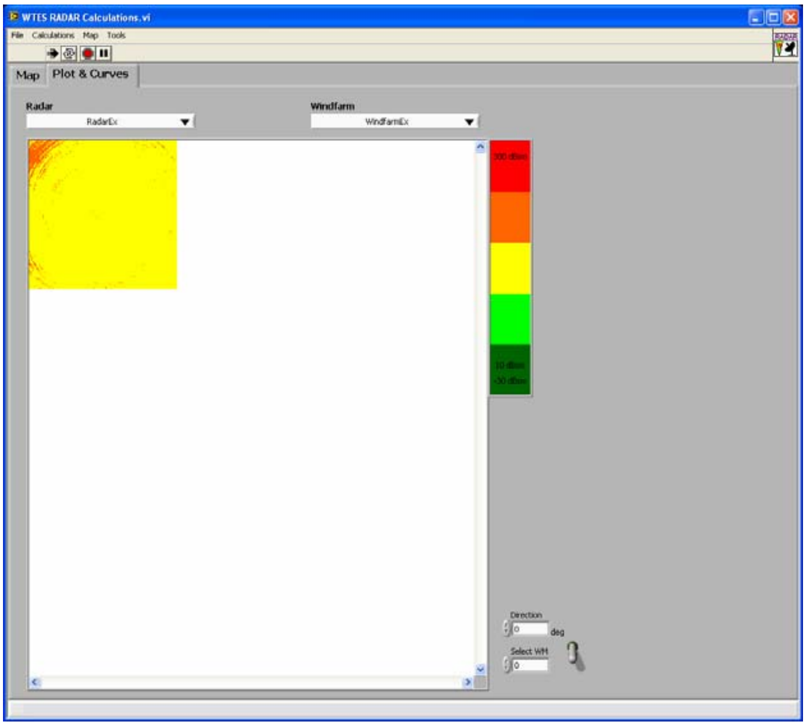


Figure 7.10 Example of Second Reflection Calculation – Target RCS mode.

The calculation is done according to a certain **target altitude**, chosen in the settings (Figure 7.12).

By selecting the mode **Target RCS**, the lowest necessary RCS value for a target, in a given altitude and position, to be detected by the radar is calculated. This is done for every position in the defined area and for each windmill. The result in each of the positions is the lowest value calculated for the different windmills. The result is divided into five levels; red, orange, yellow, light green and dark green. Green corresponds to a low necessary RCS, while red corresponds to a high necessary RCS.

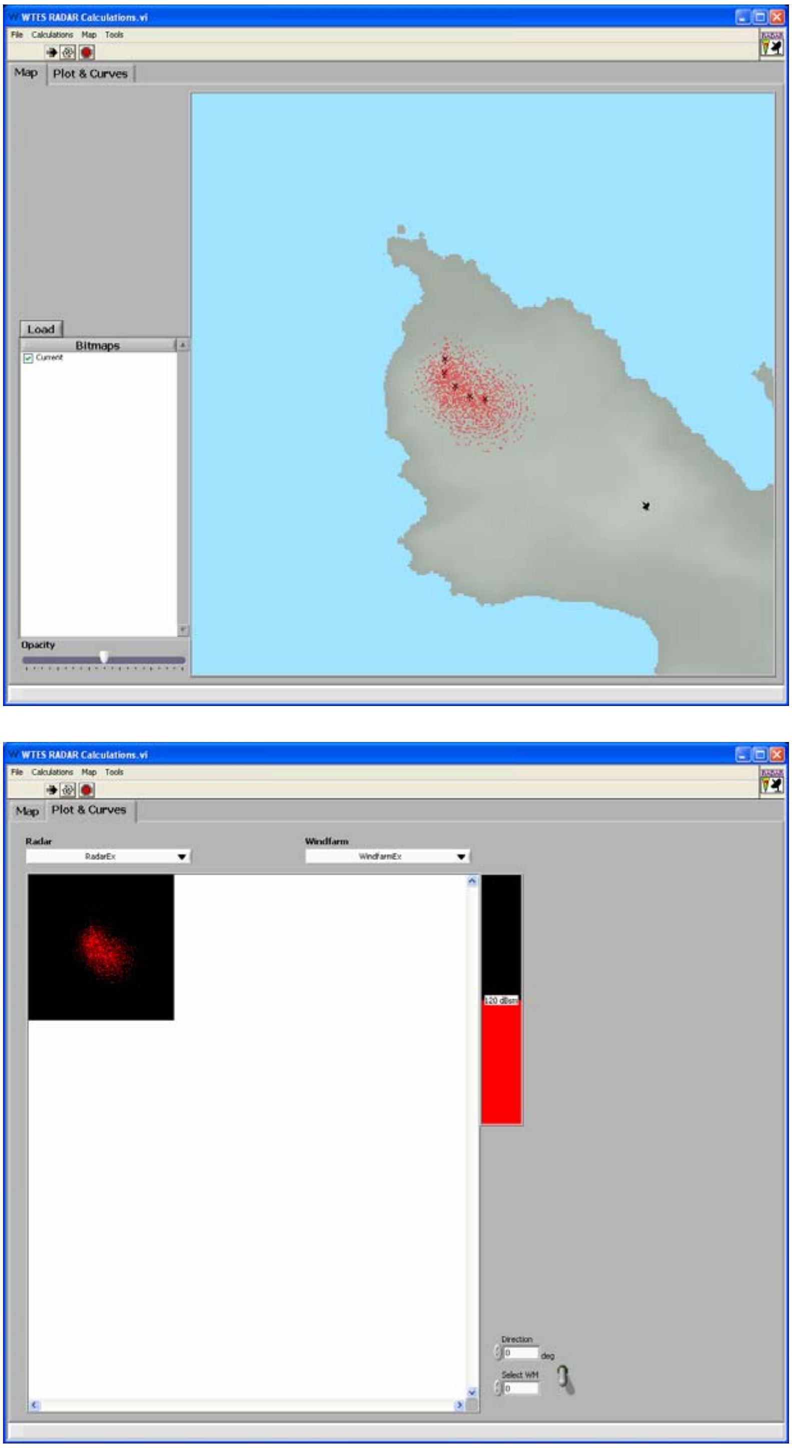


Figure 7.11 Example of Second Reflection Calculation – Ghost target detection mode.

By selecting the mode **Ghost target detection**, the calculated necessary RCS values are compared to a threshold-value, set by the Actual Target RCS in settings (see Figure 7.12). The pixels containing RCS values below the threshold are red, the other are blank. This means that targets having RCS equal to or below the threshold and being in the red positions, will generate ghost targets behind the wind park.

7.5.1 Settings

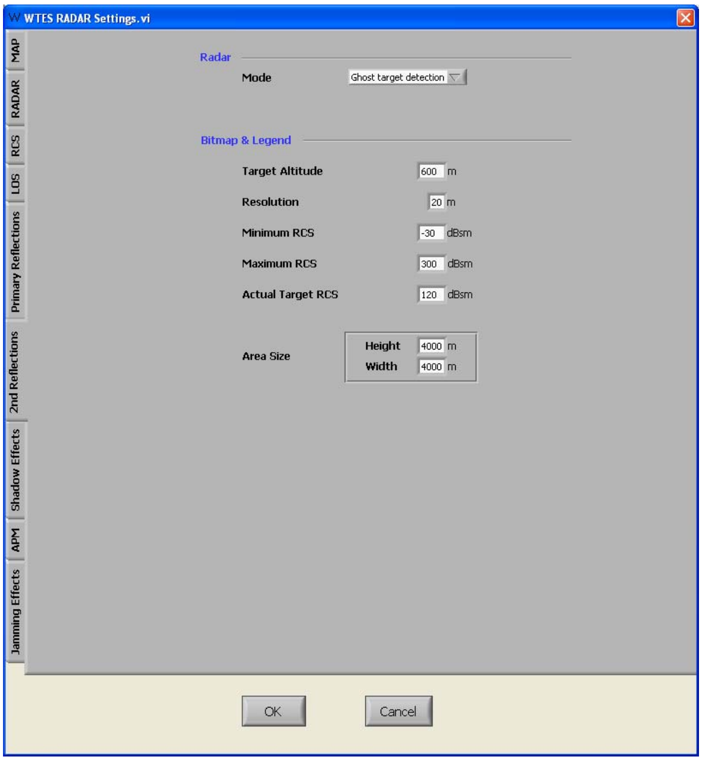


Figure 7.12 Settings for calculations of second reflections (Values used in example).

Some of the possible settings are, like seen in Figure 7.12:

- Mode:
  - Target RCS
  - Ghost Target Detection
- Target altitude
  - The calculations are done for the given target altitude. Change the parameter to make calculations for other altitudes.
- Actual Target RCS
  - The typical RCS of the interested targets. Used in the Ghost target detection mode as the threshold value.

7.6 Shadow Effects

Selecting the Shadow Effects option generates a colored bitmap showing the results of the Shadow Effects calculations. An example of a Shadow Effects calculation is shown in Figure 7.13 and Figure 7.14. The theory is described in section E and in (3).

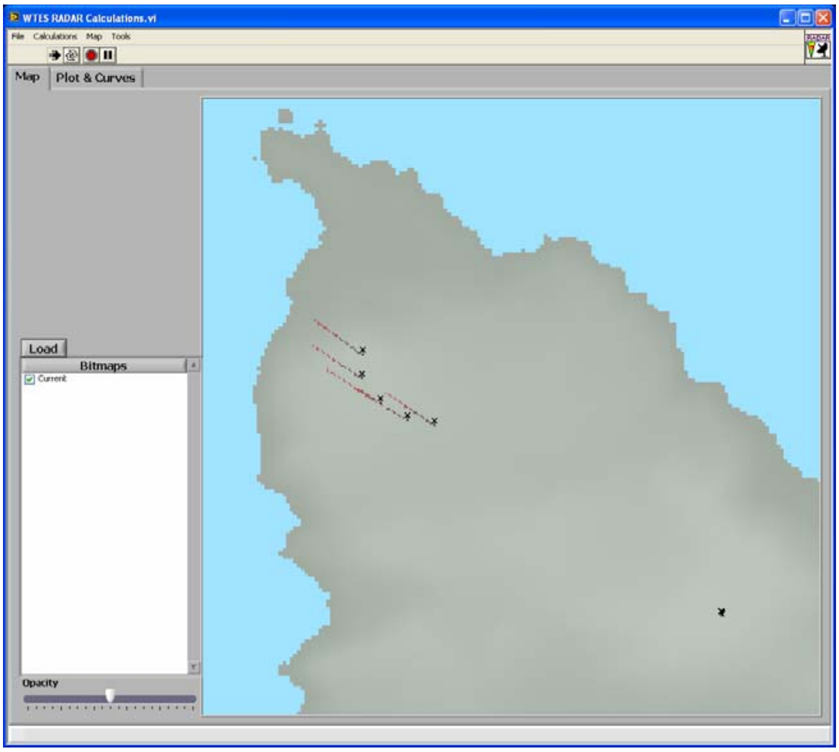
It is possible to choose between four different modes for the calculations:

1) Fast:
This is the fastest option. Calculates and plots the dark shadow region behind the windmill. Calculations are based upon Equations (E.7)-(E.17). The shadow is plotted for all wind turbines in the wind park.

2) Custom:
For showing the electromagnetic field both inside and outside of the dark shadow region, this is the fastest option. Based on the given frequency a bitmap of fixed size (500x1000 m) and resolution (2 m) is chosen from a library of previously generated bitmaps. Equations (E.1)-(E.6) have been used for the calculations. The bitmap is shown for one wind turbine, but the results are similar for the other wind turbines.

3) User Defined:
Calculates the electromagnetic field both inside and outside of the dark shadow region. Values for all parameters are set by the user (see Figure 7.15). Calculations may take from a few minutes up to several hours depending on the choice of frequency and the size and resolution of the targeted area (bitmap). Equations (E.1)-(E.6) are used in the calculations. The bitmap is shown for one wind turbine, but the results are similar for the other wind turbines.

4) User File:
Shows a previously user generated bitmap (see 3) above).



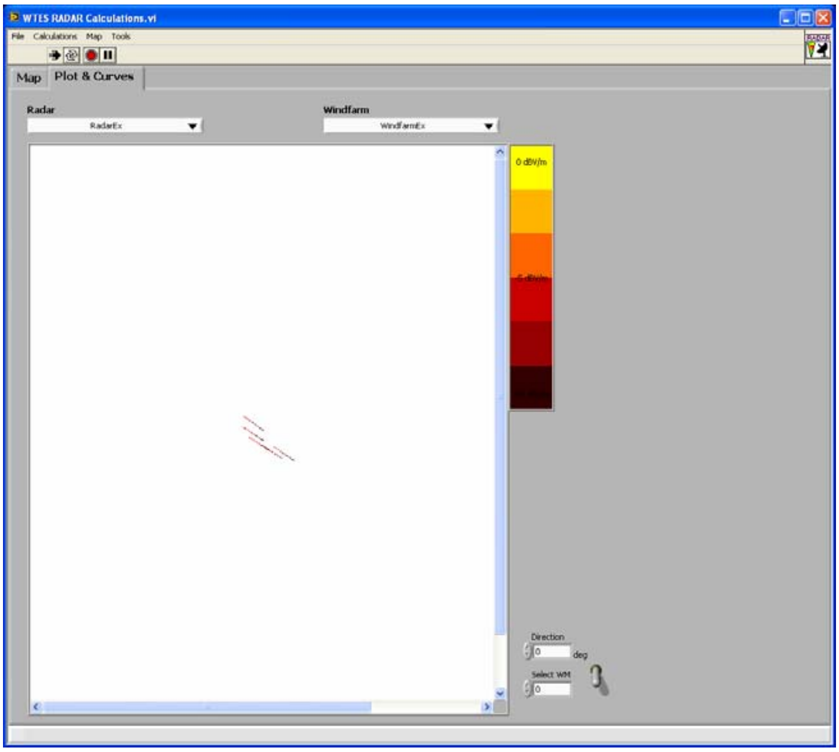


Figure 7.13 Example of Shadow Effect calculations – Fast mode selected.

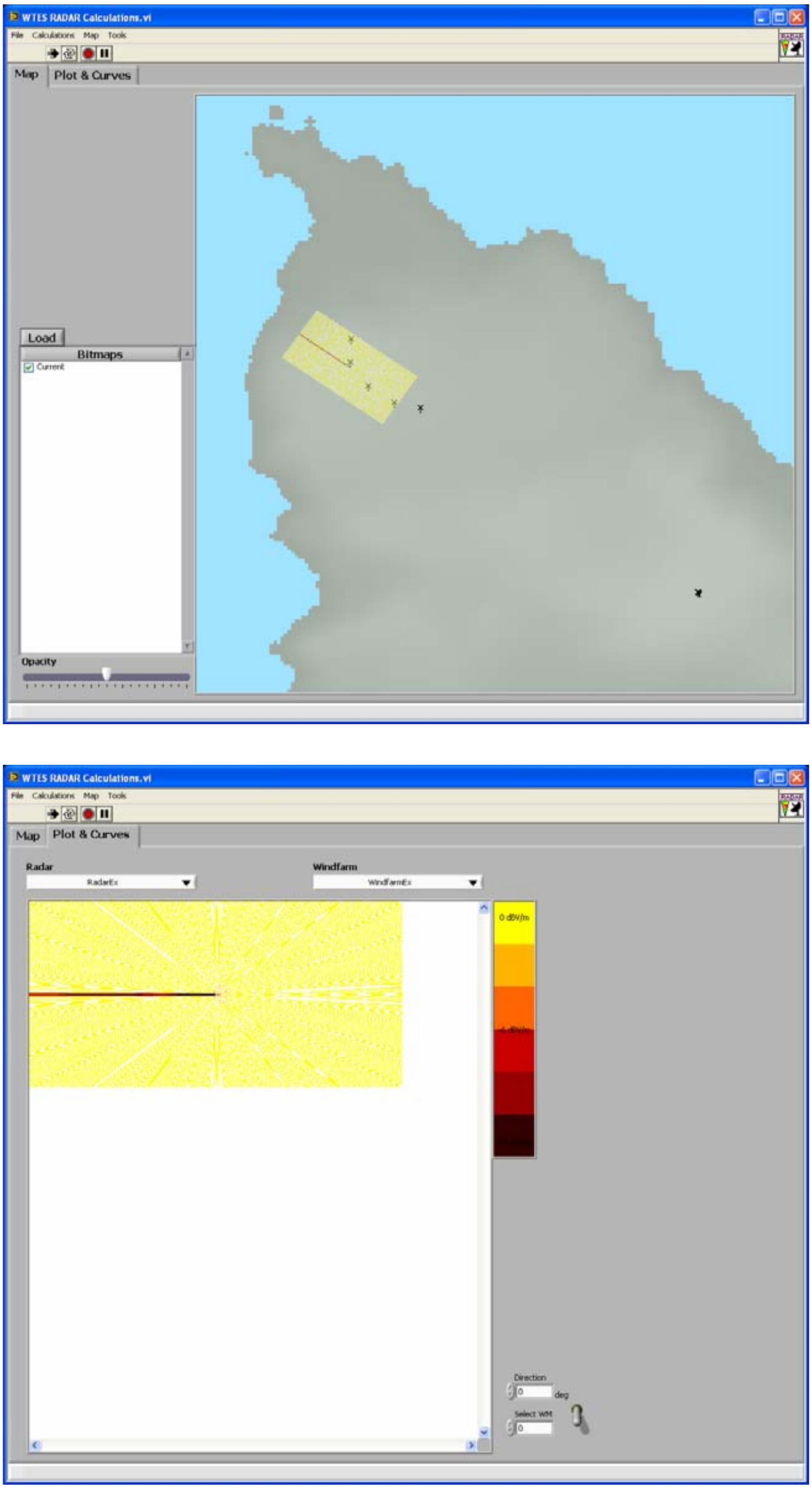


Figure 7.14 Example of a Shadow Effects calculation – Custom mode selected.

The bitmap in Figure 7.13 and Figure 7.14 shows the electromagnetic shadow behind a wind turbine. The electric field is calculated relative to the unperturbed electric field (when the wind turbine is not present). The calculations do not take into consideration interactions between the electromagnetic fields around the different wind turbines.

7.6.1 Settings

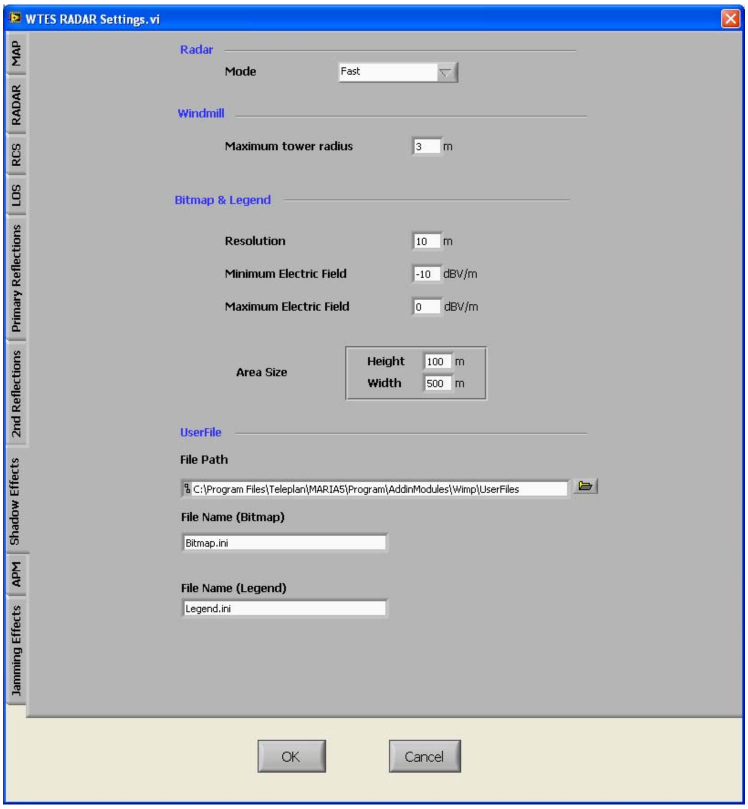


Figure 7.15 Settings for the Shadow Effects calculations (Default values).

The following settings are specific to the Shadow Effects calculations (see Figure 7.15):

- Mode (See section 7.6):
  - Fast
  - Custom
  - User defined
  - User File
- Maximum tower radius
  - Maximum tower radius (m).
- Resolution
  - Resolution of the bitmap grid (m).
- Minimum Electric Field
  - Minimum electric field displayed in the bitmap (dBV/m).
- Maximum RCS
  - Maximum electric field displayed in the bitmap (dBV/m).
- Area Size
  - Height and width of the bitmap/targeted area (m).
- User File Path
  - The path to the location that user files will be stored/retrieved from.

- User File (Bitmap)
    - Name of the bitmap-file to store/retrieve. The file name should have the file extension .ini.
- User File (Legend)
    - Name of the file that holds the values for the legend. The file name should have the file extension .ini.

7.7 APM - Advanced Propagation Model

Selecting the APM option generates a colored graph showing the results of the Advanced Propagation Model calculations. For a user guide for the external APM program, see (6). An example of an APM calculation in a Range-Height-Indicator diagram is shown in Figure 7.16, and the calculations are described in section G.

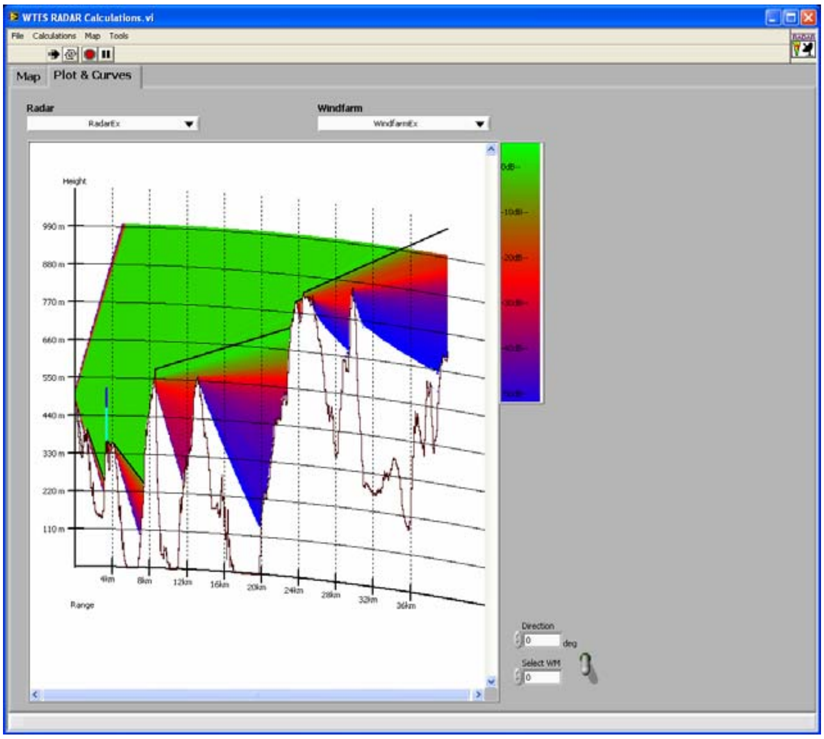


Figure 7.16 Example of APM Calculation in a RHI diagram.

The different colors correspond to the signal strength, as indicated in the legend. Some of the colors can be changed in the settings (Figure 7.17).

The calculations can be made for a given direction or in the direction of a windmill. The direction is relative to north and clockwise. Only the windmills in the chosen direction (± 0.1 rad) are plotted in the picture. If you choose to look in the direction of a windmill, only this windmill will be plotted, even if other windmills lay in the same direction.

The propagation calculations are only done due to the terrain; the windmills are only plotted onto the picture.

7.7.1 Settings

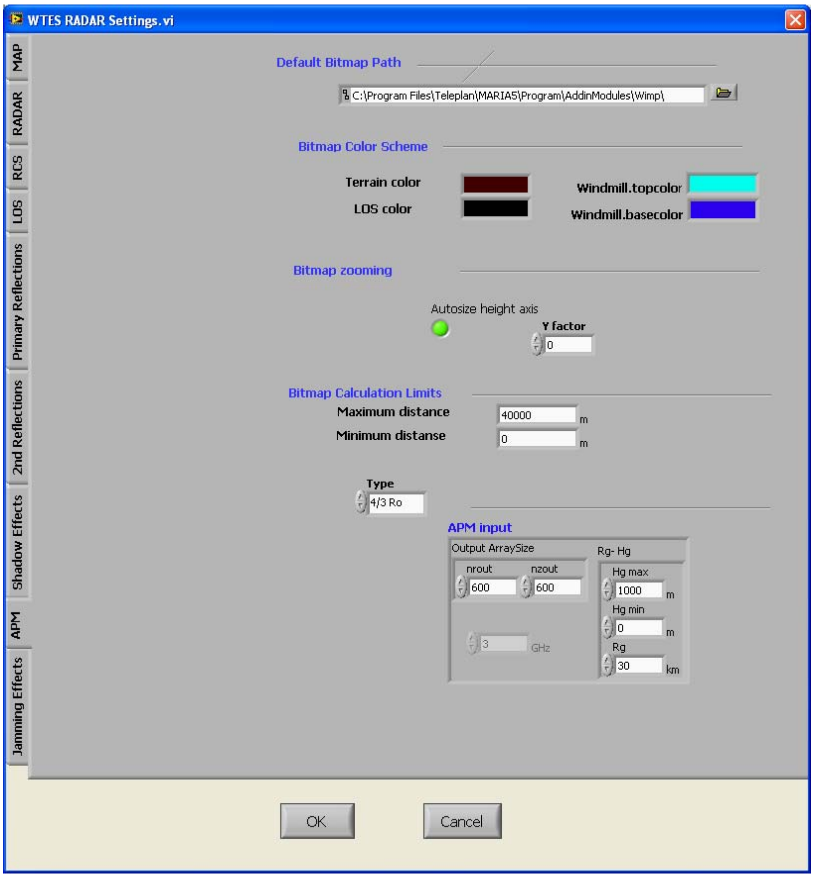


Figure 7.17 Settings for calculation of APM.

Some of the possible settings are, like seen in Figure 7.17:

- Type
  - Gives the earth radius to use for the calculations, normally 4/3 R_e is used.
- APM parameters
  - nrout = Number of range output points
  - nzout = Number of height output points
  - Frequency = Radar frequency (MHz)
  - Hg max = Maximum height output (m)
  - Hg min = Minimum height output (m)
  - Rg = Maximum range output (km)

7.8 RCS-model

Simulations are accomplished for two different generic windmills (data are given in appendix F). The program will automatically chose the predefined RCS model with best correspondence to the actual windmills.

The predefined RCS models of windmills are described in section F and (4).

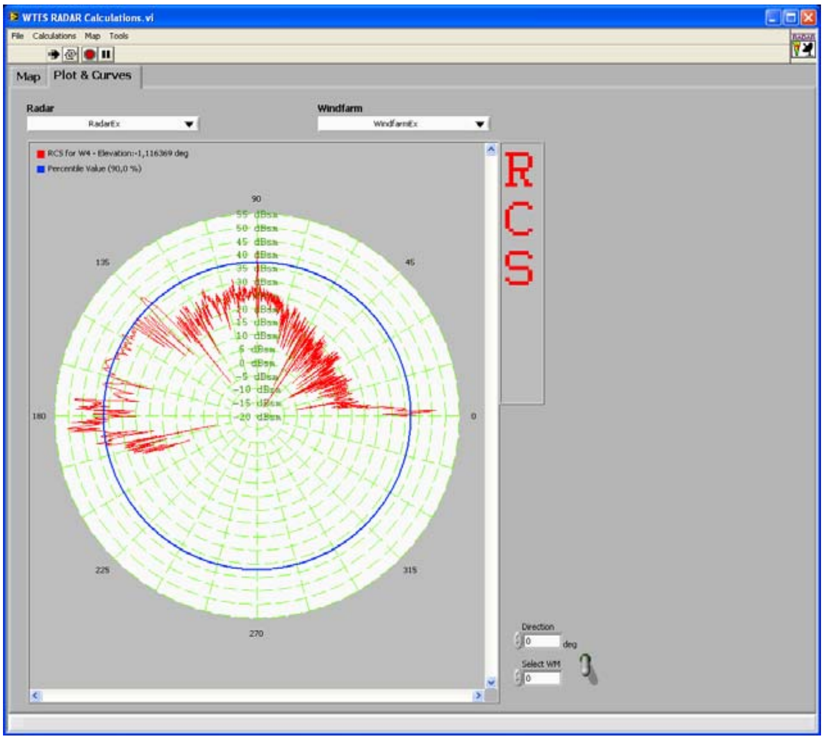


Figure 7.18 Example of RCS for a given elevation.

Select windmill (nr according to place in the xml-file) and percentile value. The program calculates the elevation angle between the radar and the chosen windmill. The RCS values for the most relevant generic windmill are shown.

7.8.1 Settings

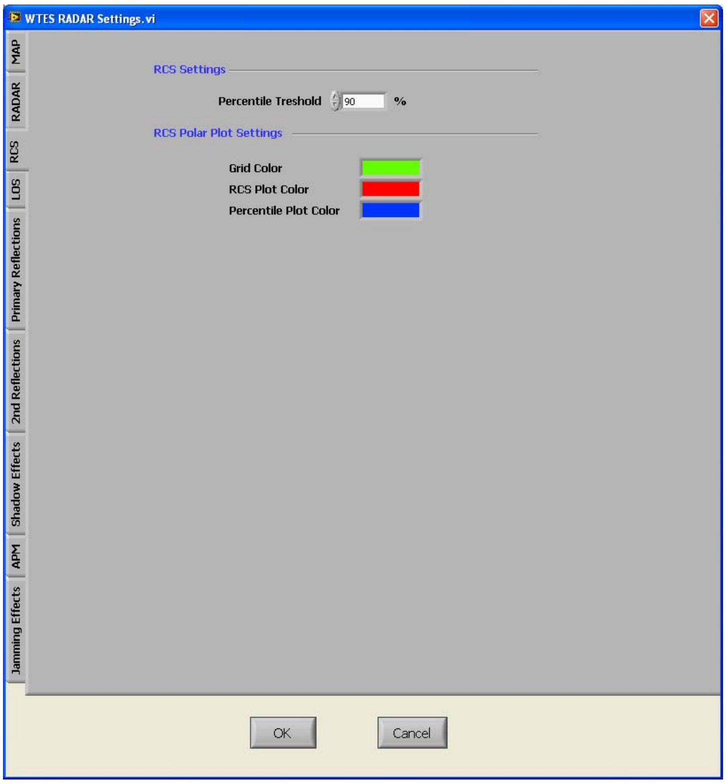


Figure 7.19 Settings for plotting of RCS data (Default values).

The possible settings for RCS calculations are, as shown in Figure 7.19:

- Percentile Threshold (%).
- Plot colours.

7.9 Jamming Effects

Selecting the Jamming Effects option generates a colored bitmap showing the results of the Jamming Effects calculations. An example of a Jamming Effects calculation is shown in Figure 7.20, and the calculations are described in section H.

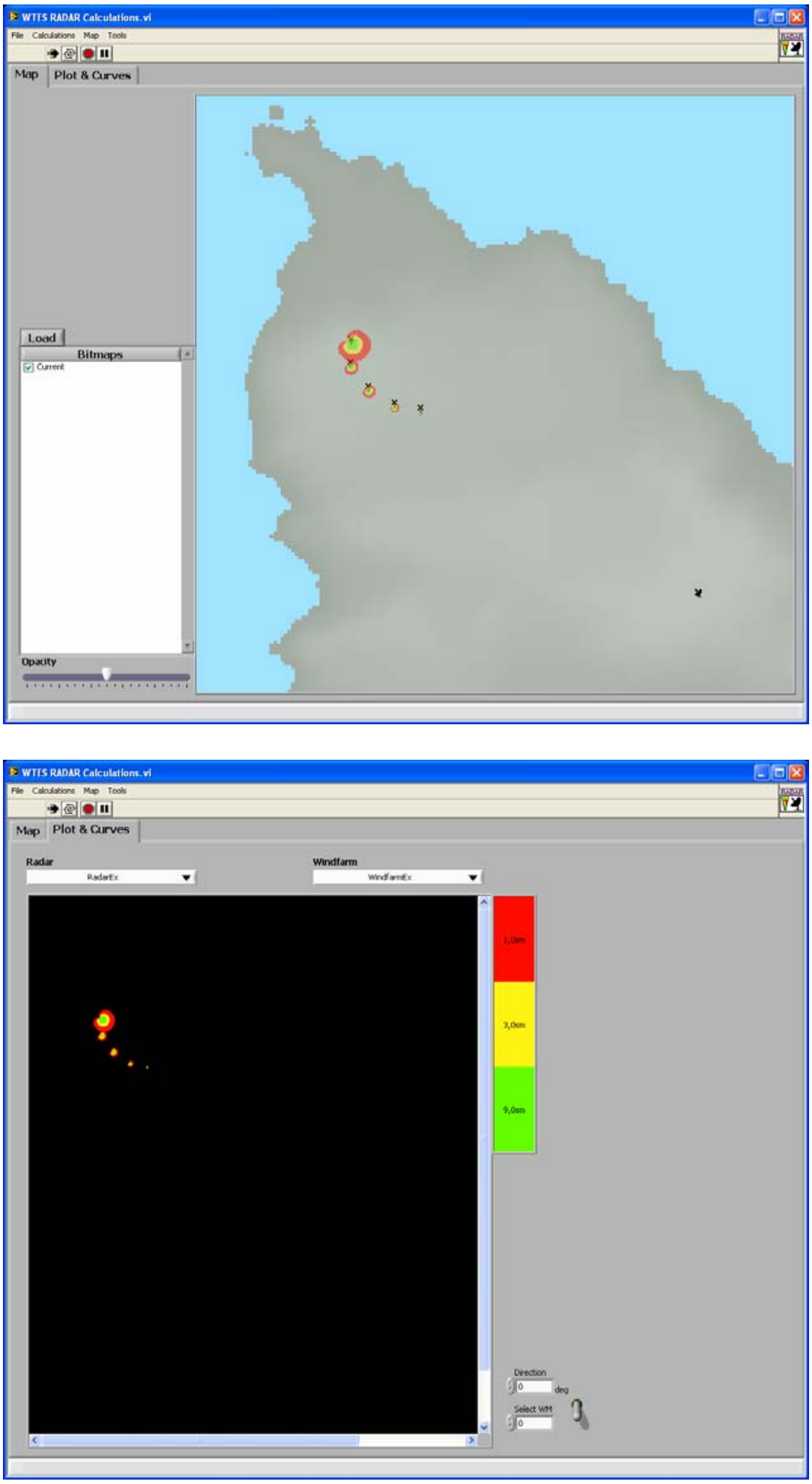


Figure 7.20 Example of Jamming Effects.

The different colors indicate the necessary RCS of a target to be detected in the different positions under influence of jamming. The settings possible to adjust, is shown in Figure 7.21.

7.9.1 Settings

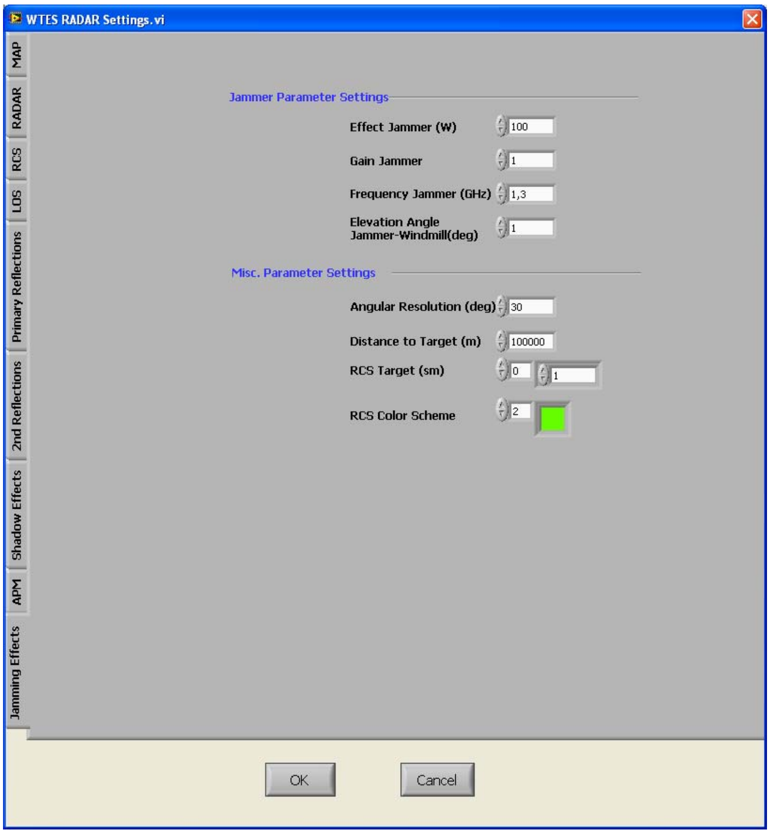


Figure 7.21 Settings for calculation of Jamming Effects.

Some of the possible settings are, like seen in Figure 7.21:

- Jamming source
  - Effect (W)
  - Gain
  - Frequency (GHz)
  - Elevation angle (Jammer-windmill) (deg)
- Miscellaneous
  - Angular resolution (deg)
  - Distance to target (m)
  - RCS of target (m^2)
  - RCS colour scheme (colour for the five levels of target RCS)

8 SECONDARY SURVEILLANCE RADAR (SSR)

Pushing the radio button for SSR gives the window shown in Figure 8.1.

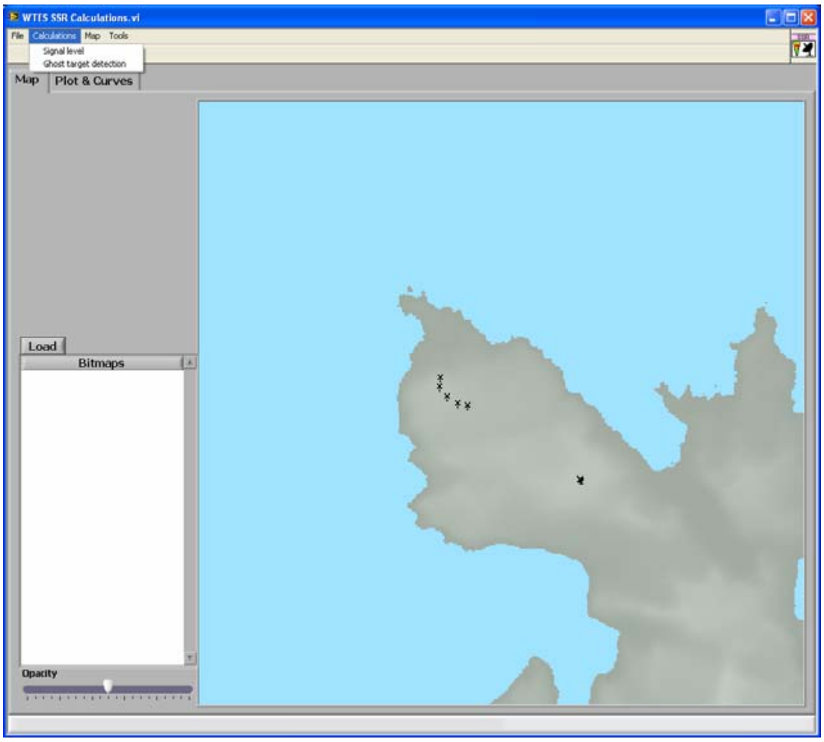


Figure 8.1 The menu window for SSR calculations and analysis

For the SSR there are two different opportunities for calculations, as described below. The description of Signal Level is found in section 8.1 and the description of Ghost Target Detection is found in section 8.2.

8.1 Signal Level

Selecting the Signal Level option generates a colored bitmap showing the results of the Signal Level calculations. An example of a Signal Level calculation is shown in Figure 8.2, and the calculations are described in section I.

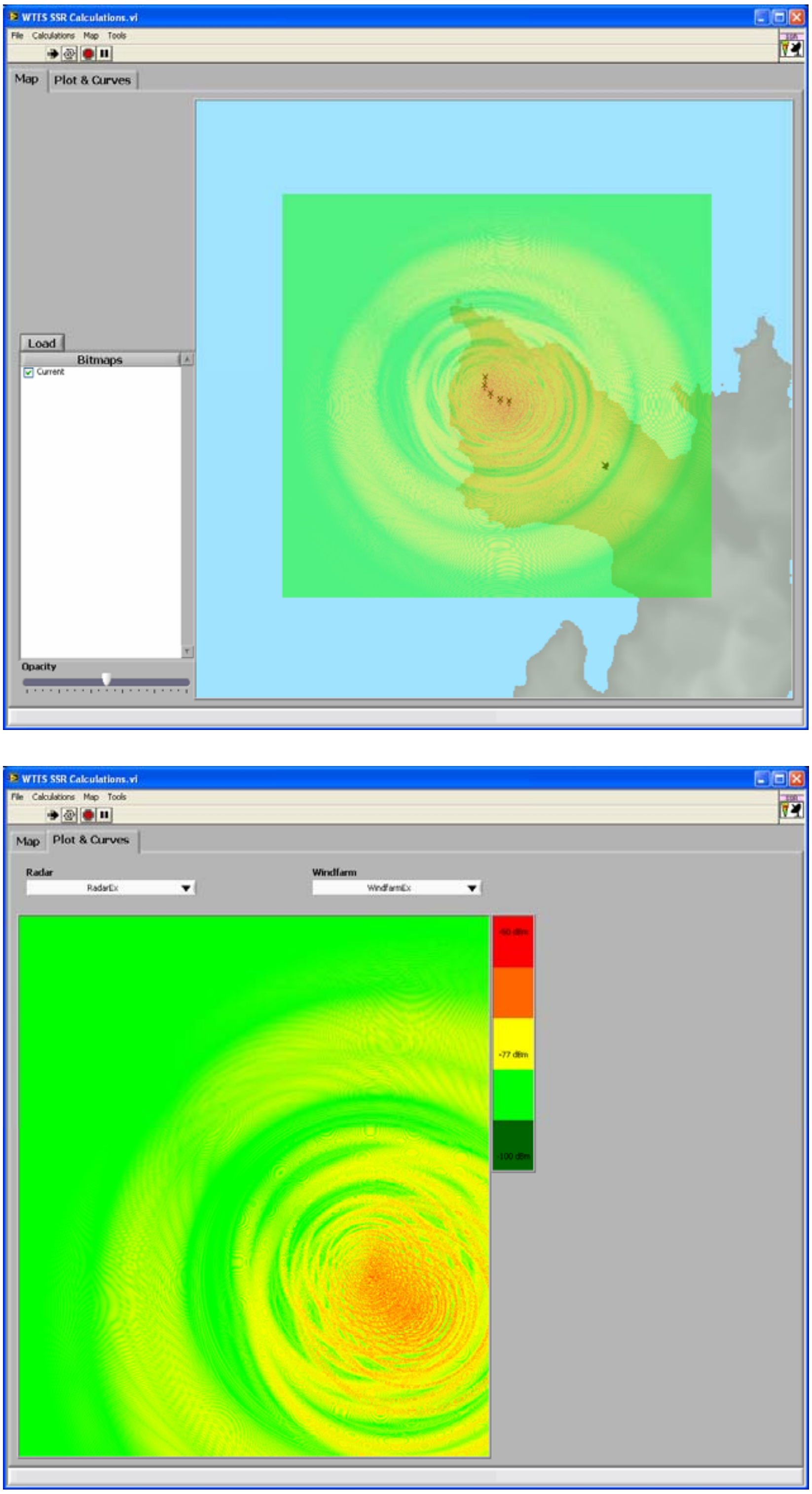
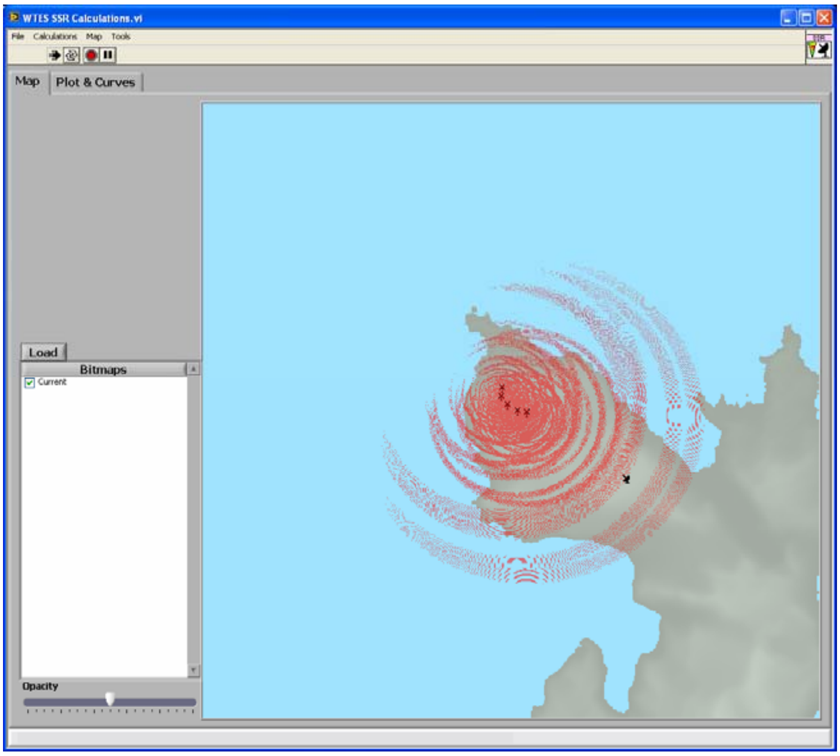


Figure 8.2 Example of Signal Level Calculation

The colours correspond to the signal level received by a target in this position according to a request from the SSR received via the wind farm. The signal strength is divided into 5 levels, and the colours are dark green, light green, yellow, orange and red (form low to high signal).

8.2 Ghost Target Detection

Selecting the Ghost Target Detection option generates a colored bitmap showing the results of the Ghost Target Detection calculations. An example of a Ghost Target Detection calculation is shown in Figure 8.3, and the calculations are described in section I.



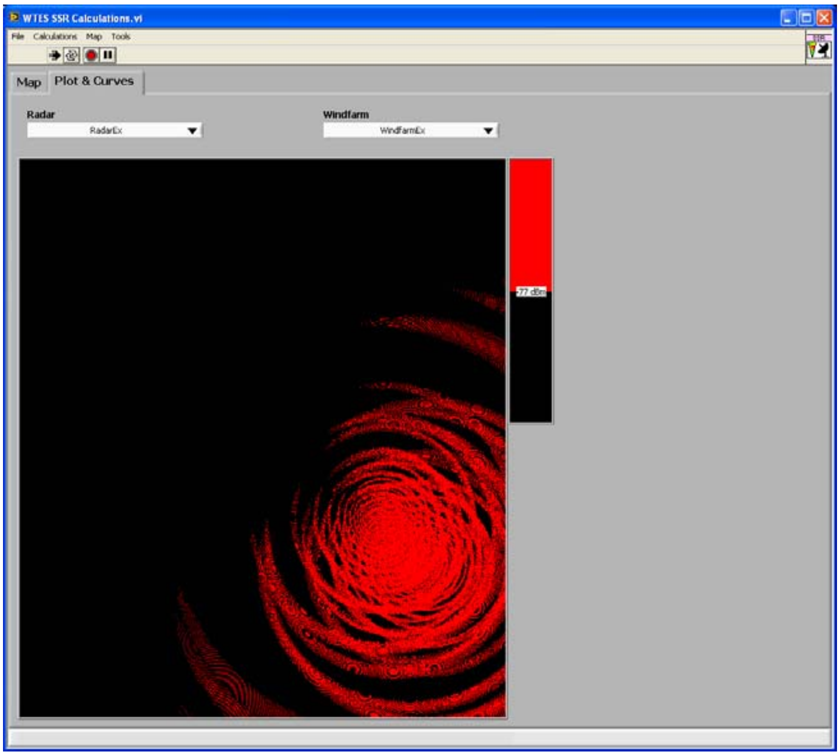


Figure 8.3 Example of Ghost Target Detection Calculation

When the signal level received by the target is above the sensitivity of the transponder, the transponder will reply, and a ghost target is detected. The true target in the indicated position will give a ghost target behind the wind farm. The sensitivity or detection threshold is given in settings (Figure 8.4).

8.3 Settings

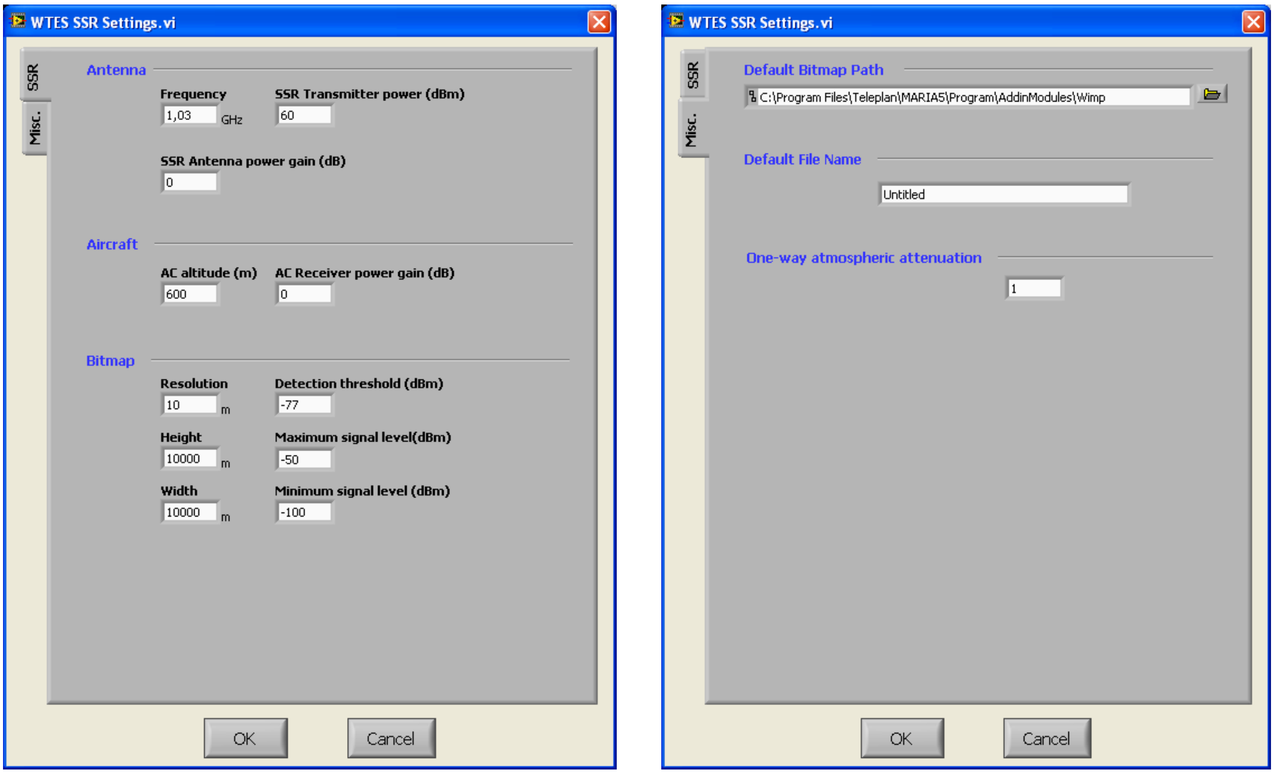


Figure 8.4 Settings for SSR calculations.

The possible settings are, like seen in Figure 8.4:

- Secondary Surveillance Radar Antenna
    - Frequency (GHz)
    - Transmitter Power (dBm)
    - Antenna Gain (dB)
- Aircraft (Target)
    - Altitude (m)
    - Receiver Gain (dB)
- Bitmap
    - Resolution (m)
    - Height and Width of the calculated bitmap (m)
    - Detection threshold (dBm)
    - Maximum signal level (dBm)
    - Minimum signal level (dBm)
- Misc
    - One-way atmospheric attenuation (dB/km)

9 PASSIVE SENSOR

Pushing the radio button for Passive Sensor gives the window shown in Figure 9.1.

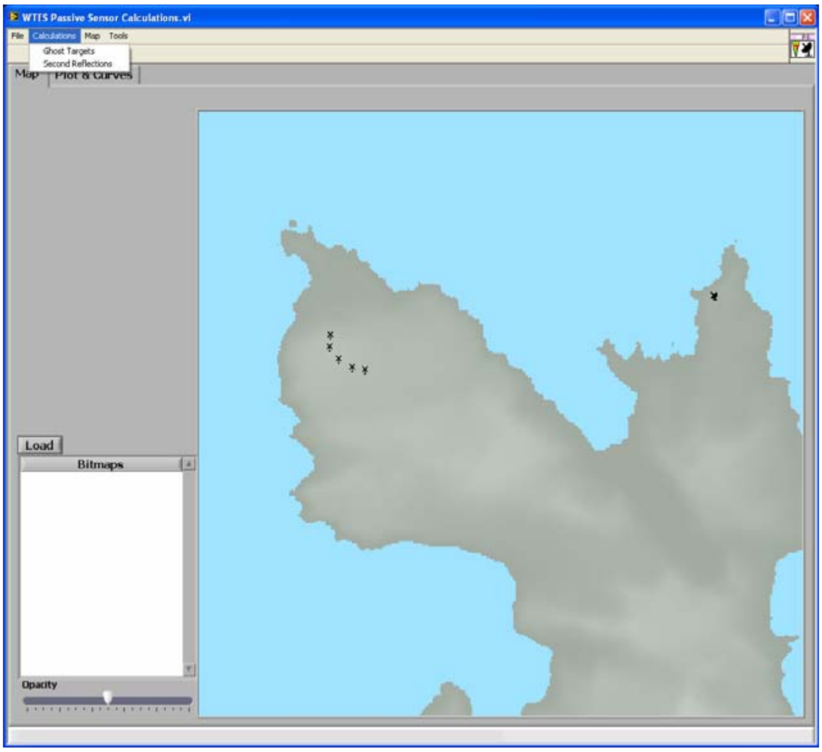


Figure 9.1 The menu window for Passive Sensor calculations and analysis

For the PS there are two different opportunities for calculations, as described below. The description of Second Reflection is found in section 9.1 and the description of Ghost Targets is found in section 9.2.

9.1 Second Reflection

Selecting the Second Reflection option generates a colored bitmap showing the results of the Second Reflection calculations. An example of a Second Reflection calculation is shown in Figure 9.2, and the calculations are described in chapter K.

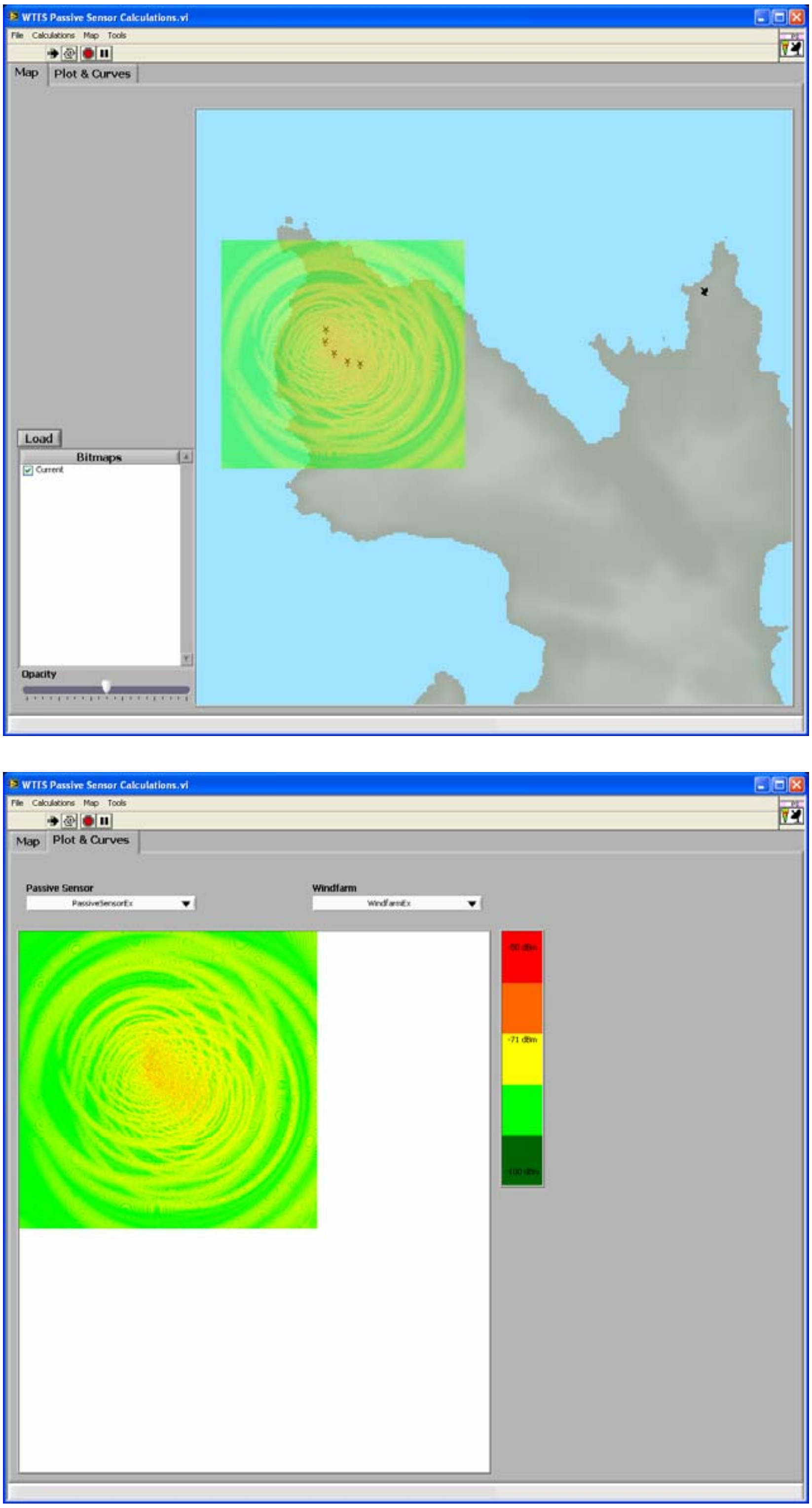


Figure 9.2 Example of Second Reflection Calculation for PS.

The signal level received at the passive sensor caused by a signal transmitted from an emitter in the actual position reflected via the wind park is calculated.

9.2 Ghost Targets

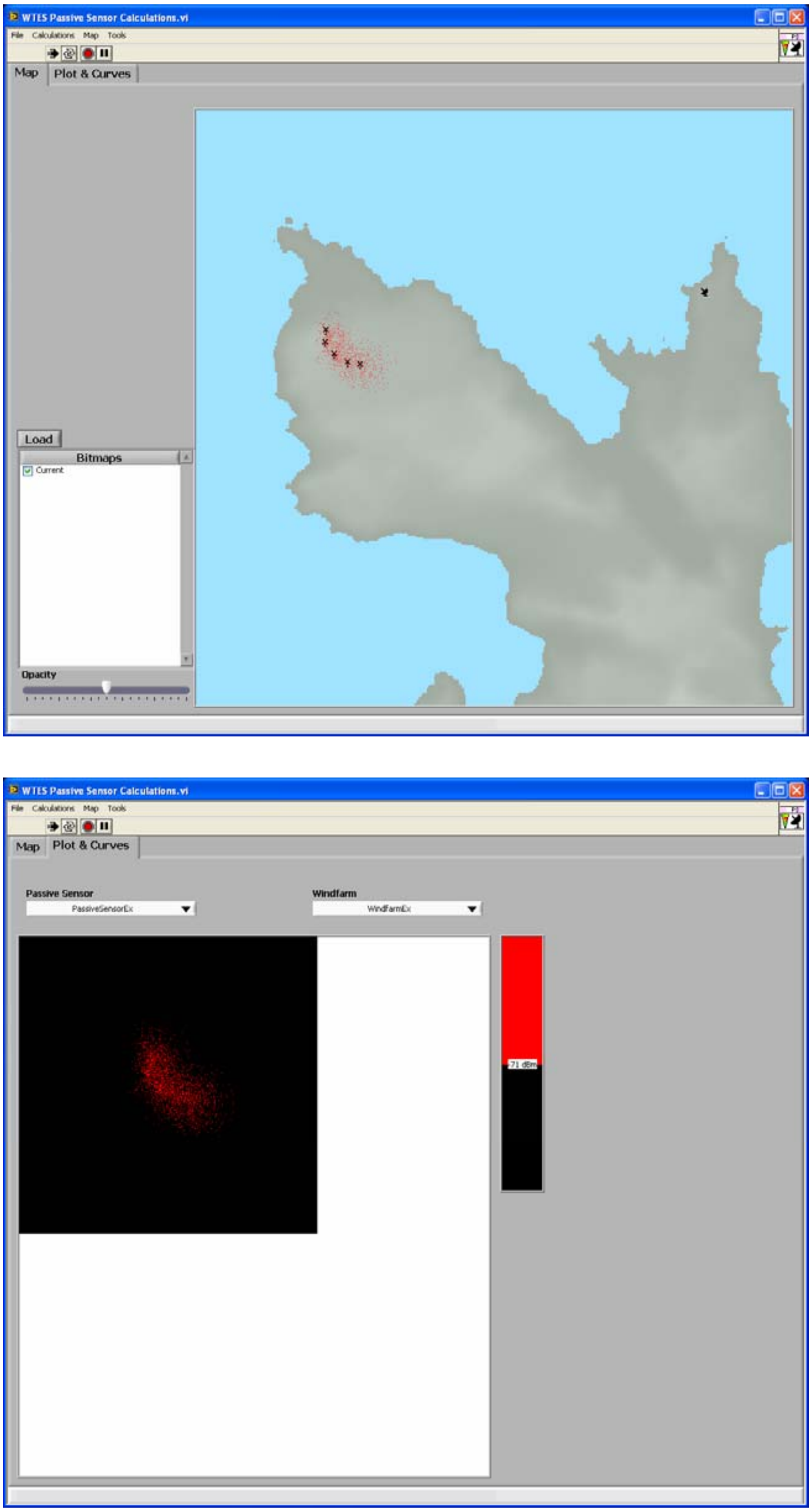


Figure 9.3 Example of Ghost Targets Calculation for PS.

For every possible emitter position, inside a defined area, the calculations give whether the signal received at the passive sensor is above the detection threshold. If so, the emitter position is shown red.

9.3 Settings

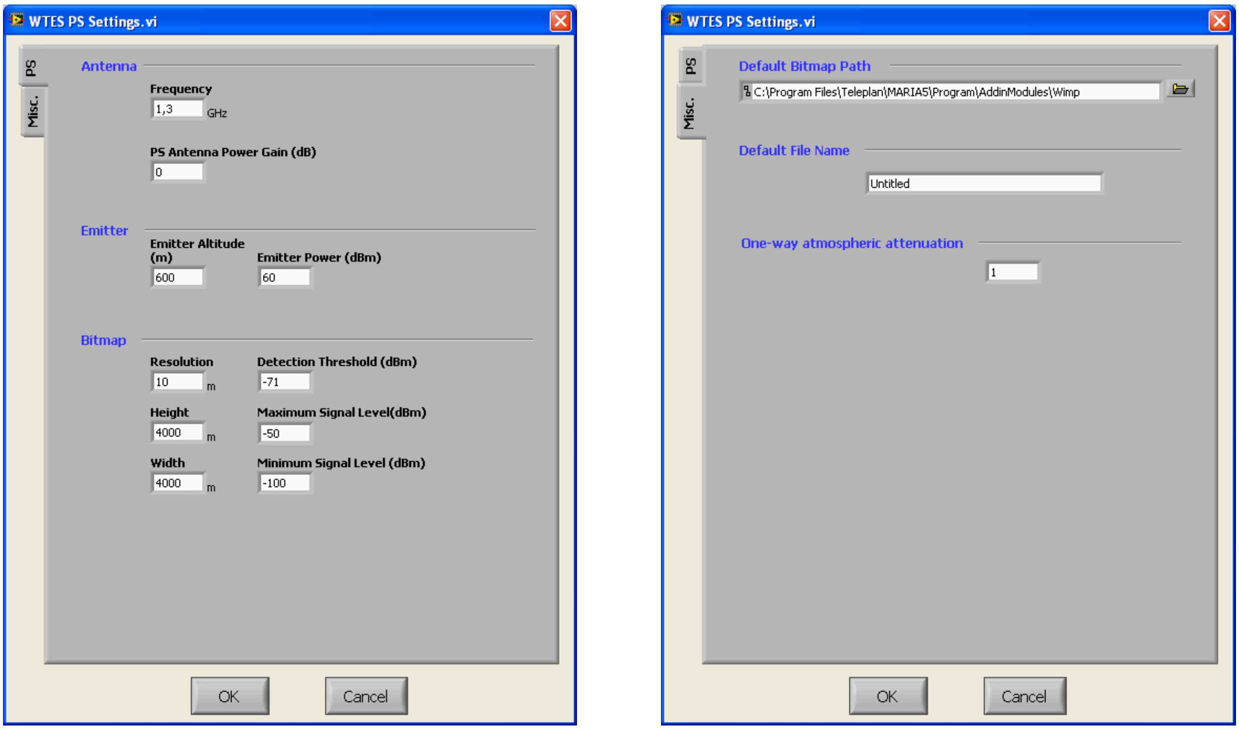


Figure 9.4 Settings for Passive Sensor calculations.

The possible settings are, like seen in Figure 9.4:

- Passive sensor antenna:
  - Frequency (GHz)
  - Antenna gain (dB)
- Emitter
  - Altitude (m)
  - Power (dBm)
- Bitmap
  - Resolution (m)
  - Area (Height and Width) (m)
  - Detection Threshold (dBm)
  - Signal level interval (min and max) (dBm)

- Misc
  - One-way atmospheric attenuation (dB/km)

10 RADIO LINK

Pushing the radio button for Radio Link gives the window shown in Figure 10.1.

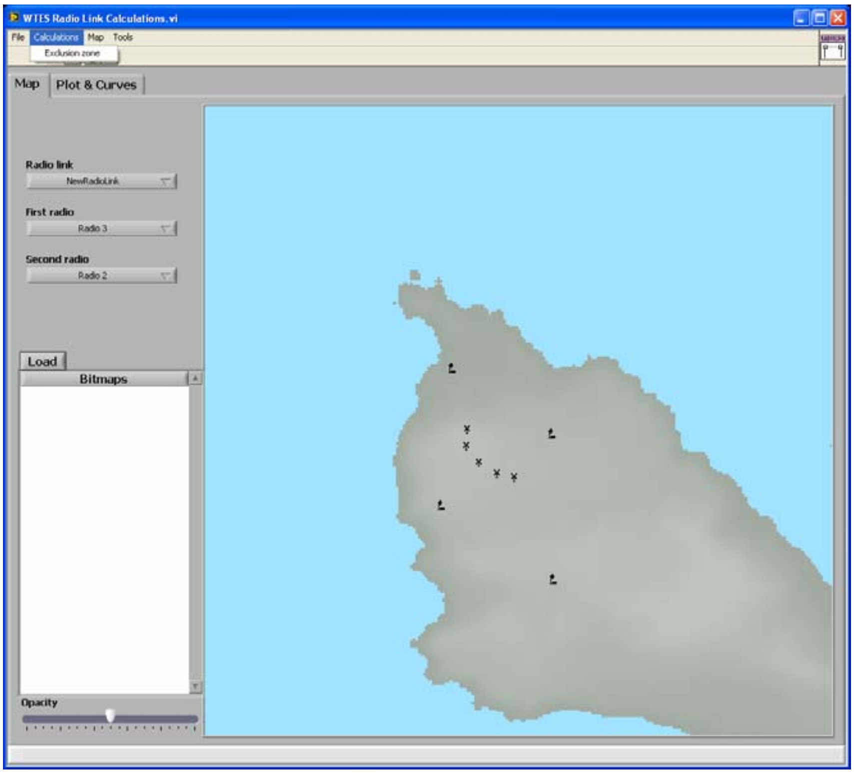


Figure 10.1 The menu window for Radio Link calculations and analysis

10.1.1 Exclusion Zones

Selecting the Exclusion Zones option generates a colored bitmap showing the results of the Exclusion Zones calculations. An example of an Exclusion Zones calculation is shown in Figure 10.2, and the calculations are described in section J.

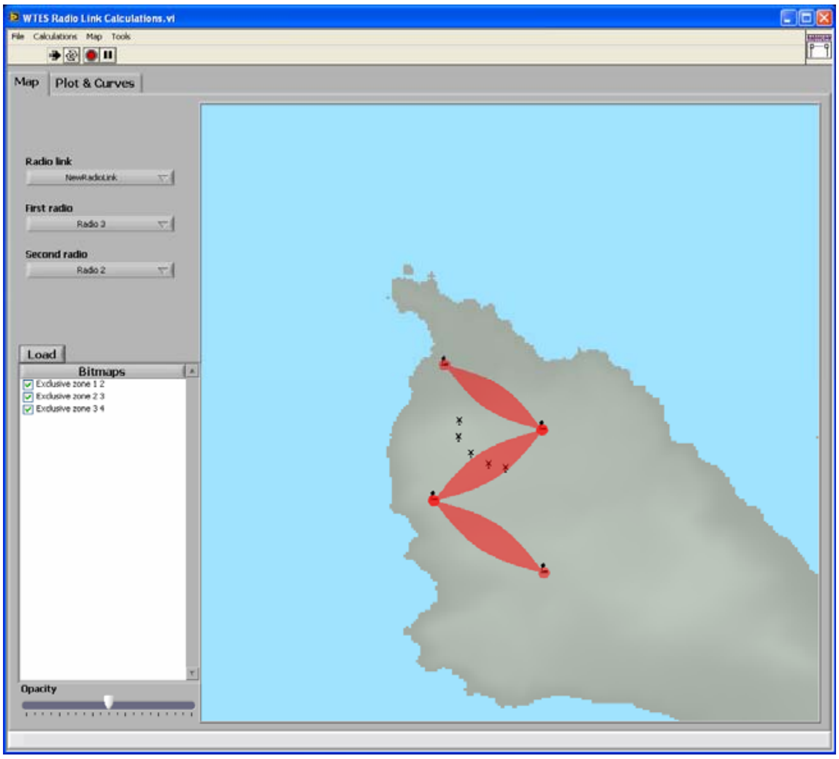


Figure 10.2 Example of Exclusion Zones Calculation

The exclusion zones are composed of a near field area around each radio (see section J.1) and a fresnel zone around the link (see section J.2 and J.3). To avoid corruption of the signal, the signal path directly between the radios and the signal path via the windmill should differ less than λ (se equation (J.)).

To avoid signal corruption or obstruction, the windmills must be outside the read area.

10.2 Settings

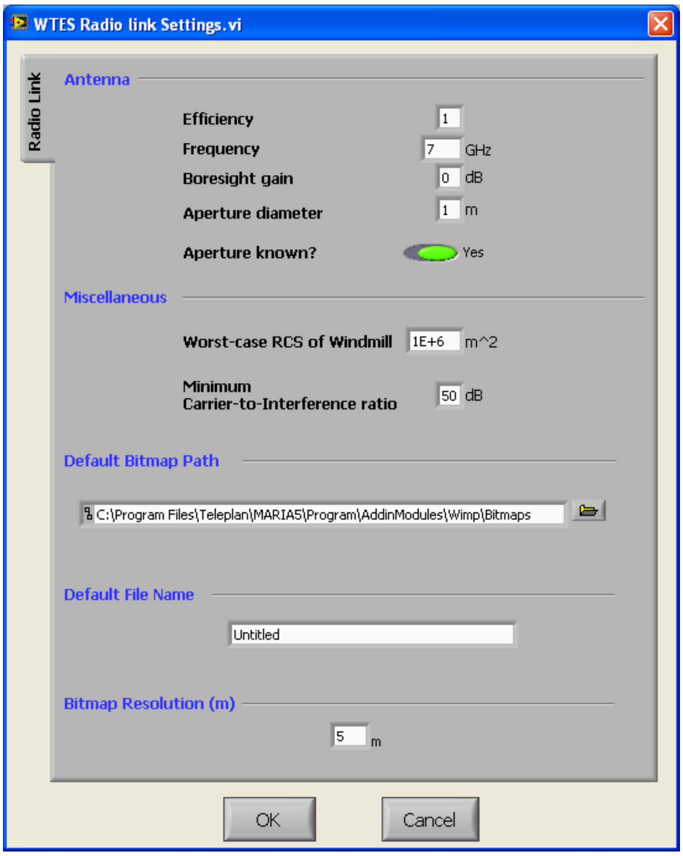


Figure 10.3 Settings for calculation of Exclusion Zones.

The possible settings are, like seen in Figure 10.3:

- The Radio Antenna
  - Efficiency (between 0 and 1)
  - Frequency (GHz)
  - Boresight Gain (dB)
  - Aperture diameter (m)
  - Aperture known (yes/no)
- Miscellaneous
  - Worst-case RCS of Windmill (m^2)
  - Minimum Carrier-to-Interference ratio (dB)
- Bitmap
  - Resolution (m)

11 HIGH FREQUENCY (HF)

Pushing the radio button for HF gives the window shown in Figure 11.1.

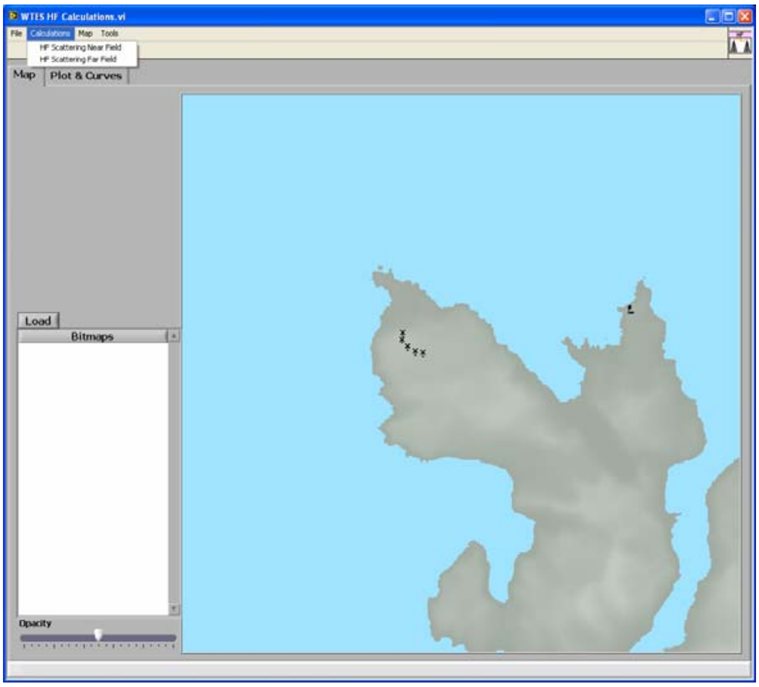


Figure 11.1 The menu window for HF calculations and analysis

The HF module applies to passive sensors in the frequency range 740 kHz – 30 MHz. Passive sensors in higher frequency bands should be handled by the Passive sensor module.

11.1 HF Scattering – far field

Selecting the HF Scattering Far Field option generates a colored bitmap showing the results of the far field calculations. An example of a HF Scattering Far Field is shown in Figure 11.2, and the calculations are described in (7) and (8).

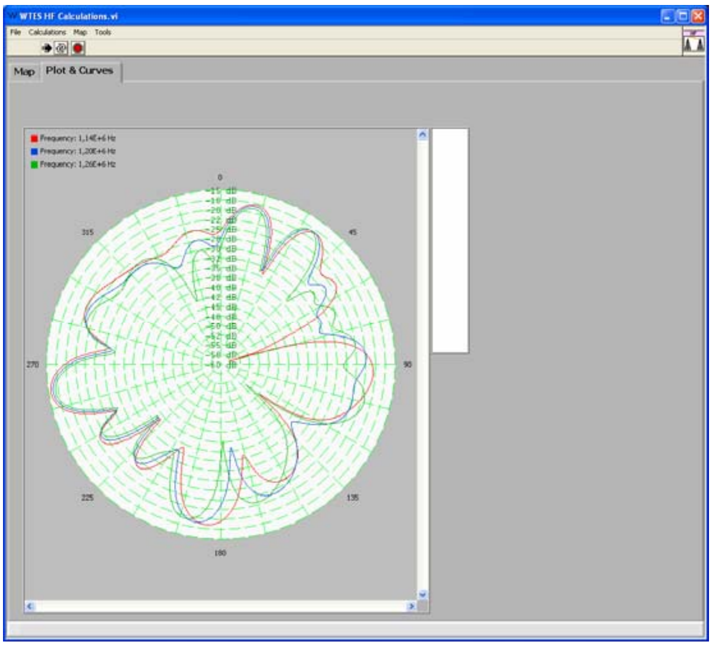


Figure 11.2 Example of HF Scattering Far Field Calculation

Presented bitmap for far field calculations shows the ratio Ks between the direct scattered signal and the reflected signal in dB. The far field bitmap show Ks as a function of azimuth angle of incidence (0 = North, 90 = East).

11.2 HF Scattering – near field

Selecting the HF Scattering Near Field option generates a colored bitmap showing the results of the near field calculations. An example of a HF Scattering Near Field is shown in Figure 11.3, and the calculations are described in (7) and (8).

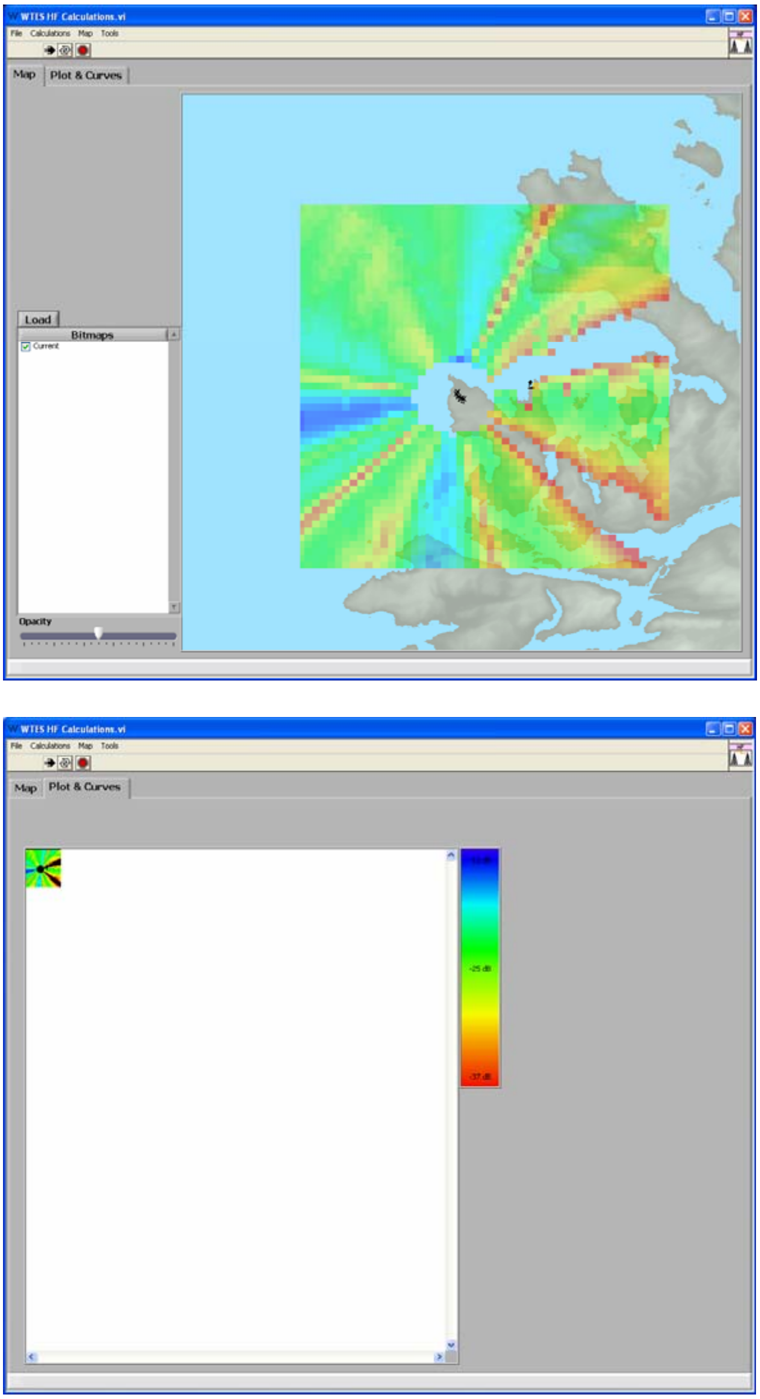


Figure 11.3   Example of HF Scattering Near Field Calculation

Presented bitmap for near field calculations shows the ratio Ks between direct scattered signal and the reflected signal in dB. The near field bitmap gives Ks as a function of azimuth angle of incidence and Tx position within the inner area.

11.3 Settings

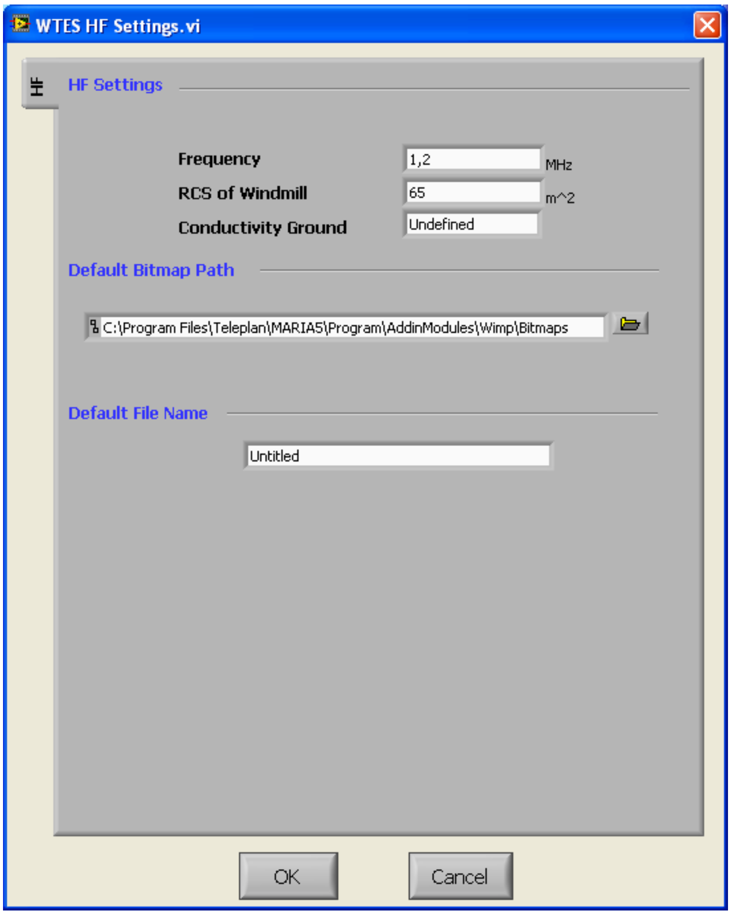


Figure 11.4 Settings for HF Scattering calculations (Default values).

The possible settings are, like seen in Figure 11.4:

- Frequency (740 kHz – 30 MHz)
- RCS of windmill
- Conductivity Ground (mS/m^2)(see Figure L.)

As long as the parameter Conductivity Ground is Undefined, the program will prompt the user to select one of the valid values. Valid values for Norway is (see Figure L.1):

- 0,0001
- 0,0003
- 0,001
- 0,003
- 0,01
- 0,03
- 5

12 SUMMARY

This report describes the software tool WTES developed at FFI to assist the Norwegian Defense in the management of Wind Turbine development applications.

The software tool will support the consideration of the applications for the Defence based on the theoretical presumption described in the latter chapters. The software will not give the answer of the application, but will give the action officer a better qualification to make the decisions.

13 ACKNOWLEDGEMENTS

The authors wish to extend their thanks to the following persons: Hans Øhra who initiated the project and was the project manager from the start in November 2004 until October 2006, Morten Søderblom at FFI who simulated the RCS data and Roald Otnes for developing the models for HF scattering. We also wish to thank the "Tiger Team" established in December 2006 to support the project in the final month. The FFI internal team was consisting of Svein-Erik Hamran, Terje Johnsen, Trygve Sparr, Aanund Storhaug, Steffen Tollisen and Stein Kristoffersen.

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A GEOMETRY

The basic calculations of geometry are mostly organized in the library files. Positions are given in latitude, longitude and height of WGS84.

A.1 Line-of-sight (LOS)

LOS is calculated based on dted height data. The LabVIEW program gathers height profile data for an area as shown in Figure A.1. The data must be collected with dense sampling in angle. For each height profile, calculations are made step by step to estimate the highest point possibly seen by the radar. The principle of screened height is shown in Figure A.2.

The LOS calculations does not account for the radar signal propagation. the propagation effects are given by the APM module (see section 7.7).

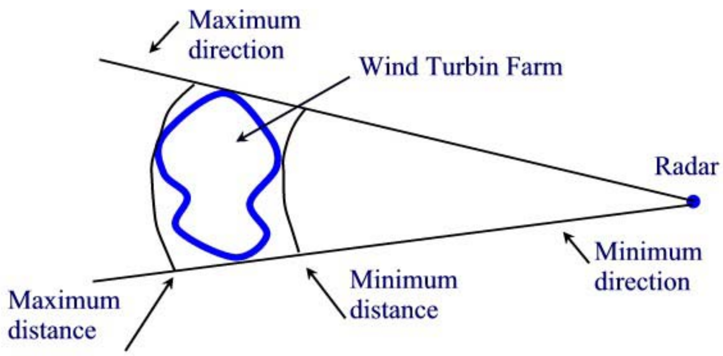


Figure A.1 Start and stop angle for the area seen from the radar.

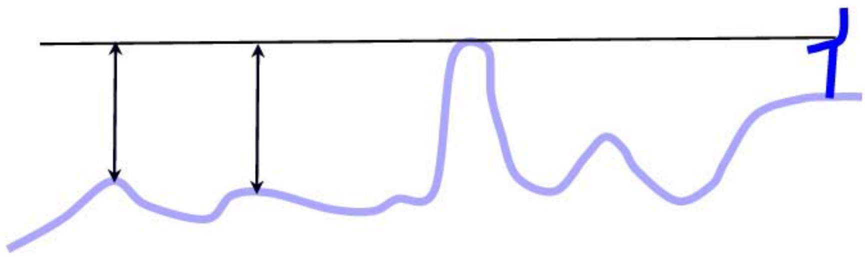


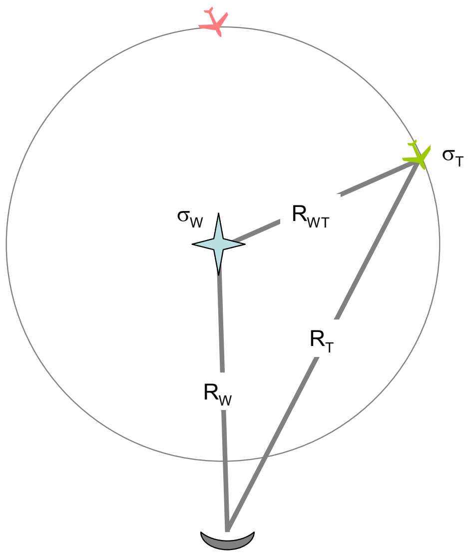
Figure A.2 The principle of screened height.

B RADAR IMPACT OVERVIEW

The WF Impact Overview module encompasses two effects that windmills may have on a radar:

1. Reflections via the windmill park where real targets may result in false targets with apparent different position than the original target.
2. Increased clutter levels in automatic detection processing such as clutter maps and CFAR.

The first situation is illustrated in Figure B., where a reflection of the radar Tx signal via the windmill (blue star, σ_W), to the real target (green target, σ_T), and back via the windmill results in a false target at a position directly behind the windmill (pink target).



$$P_{RT} = \frac{ERP}{(4\pi R_T^2)^2}\sigma_T$$

$$P_{RWT} = \frac{ERP}{4\pi R_W^2}\sigma_{WT}\frac{1}{4\pi R_{WT}^2}\sigma_T\frac{1}{4\pi R_{TW}^2}\sigma_{TW}\frac{1}{4\pi R_W^2}$$
$$= \frac{ERP\cdot\sigma_T\sigma_{WT}^2}{(4\pi)^4 R_W^4 R_{WT}^4}$$

$$\frac{P_{RWT}}{P_{RT}} = \frac{R_T^4}{(4\pi)^2 R_W^4 R_{WT}^4}\sigma_{WT}^2 = \frac{R_T^4}{R_{WT}^4}\frac{\sigma_{WT}^2}{(4\pi)^2 R_W^4}$$

Figure B.1 Reflections via windmill.

Figure B.1 also contains the equations to calculate the relative received power level from the double reflection case, P_{RWT}/P_{RT}. P_{RWT}/P_{RT} is the power received via the double reflection when the antenna points at the windmill, relative to the power received from the direct path to the target when the antenna points directly at the target. It is a measure of how strong a false target a given real target may produce.

P_{RWT}/P_{RT} = -30dB means that a target in this position with an RCS of 30dBsm would result in a false target behind the windmills of 0dBsm. A reasonable threshold for P_{RWT}/P_{RT} could be -50 dB, which means a 10.000 m^2 real target could result in 0,1 m^2 false target in another position.

The equations above (Figure B.) does not take into account the fact that many radars adjust their sensitivity as a function of the range to a target, so called STC – Sensitivity Time Control. The range to the real target generating the false target is generally shorter than the range to the false target, so the power ratio of Figure B. should be adjusted with the appropriate range factor. Assuming a perfect R^4 STC regime, P_{RWT}/P_{RT} should be multiplied by $(R_W + R_{WT})^4/R_T{}^4$.

Figure B.2 shows a calculation of the equations above using σ_w = 50 dBsm. The radar is at (0,0) and the windmill park is at (10, 10) km. Figure B. shows that only real targets within a few kilometres from the windmill park can generate false targets above the -50 dB threshold.

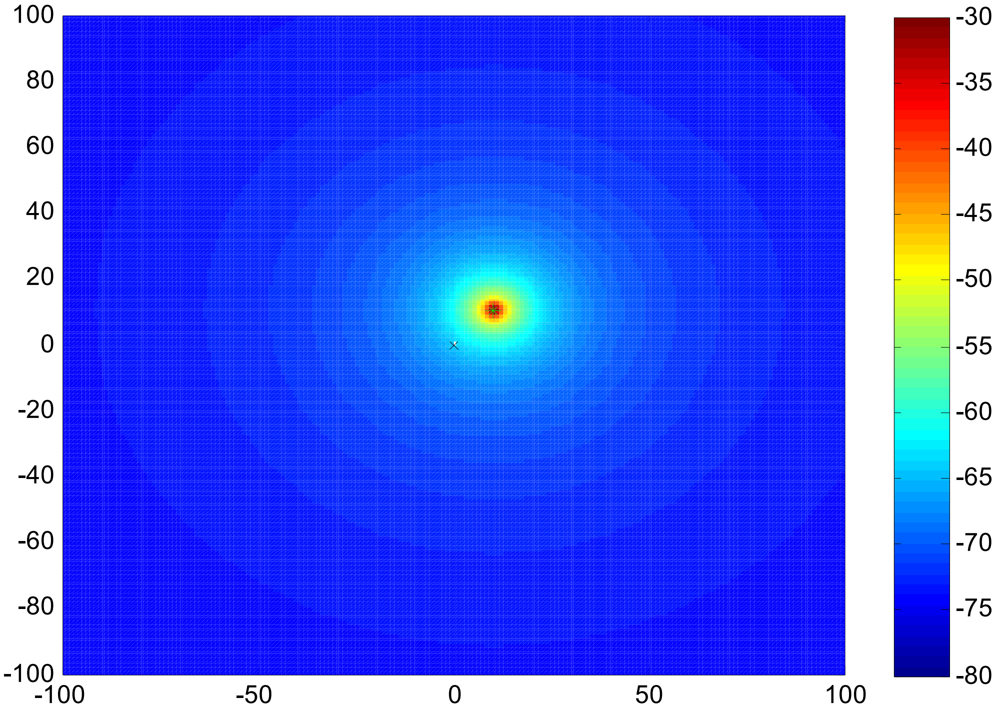


Figure B.2 Relative received power from a double reflection via windmill park, 16 incoherently added windmills of 50 dBsm at 14,1 km range from the radar.

Figure B.3 shows the same situation, but now with the windmill park at longer range; (50, 50) km. As can be seen, the area where the received power is above the -50 dB threshold is similar in size. The apparent low dependence on the range to the windmill park results from the STC.

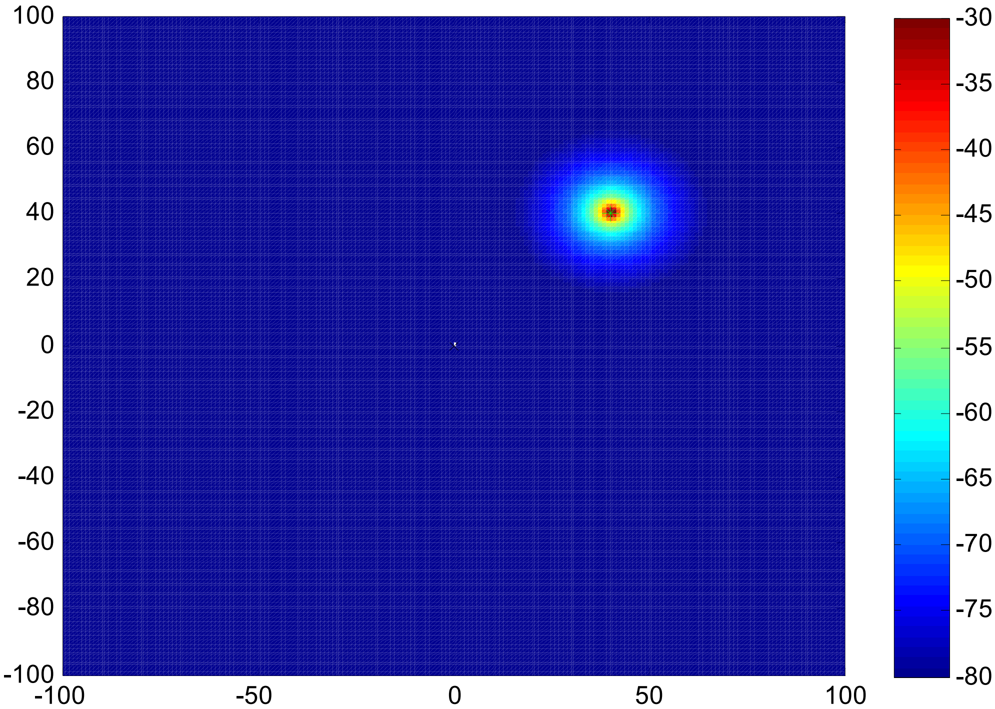


Figure B.3 Relative received power from a double reflection via windmill park, 16 incoherently added windmills of 50 dBsm at 14,1 km range from the radar.

The second effect, windmill effects on detection processing, will be seen when the windmill park produces increased clutter levels in clutter maps or CFAR noise level estimation. This is not analyzed in detail here. Rather, some assumptions are described that result in course estimates on the effects that might be seen on a specific radar. These assumptions are:

- Radar detection will be severely affected when windmills are present in the cluttermap or CFAR background level estimation calculations.
- Windmills are present in these calculations for targets appearing within one cluttermap or CFAR resolution cell to either side of the windmill park.
- Cluttermap and CFAR resolution cells can be described using a fixed range and azimuth value, and defaults of ± 1 km in range and ± one antenna beamwith in azimuth are reasonable.

The above is illustrated in Figure B.44.

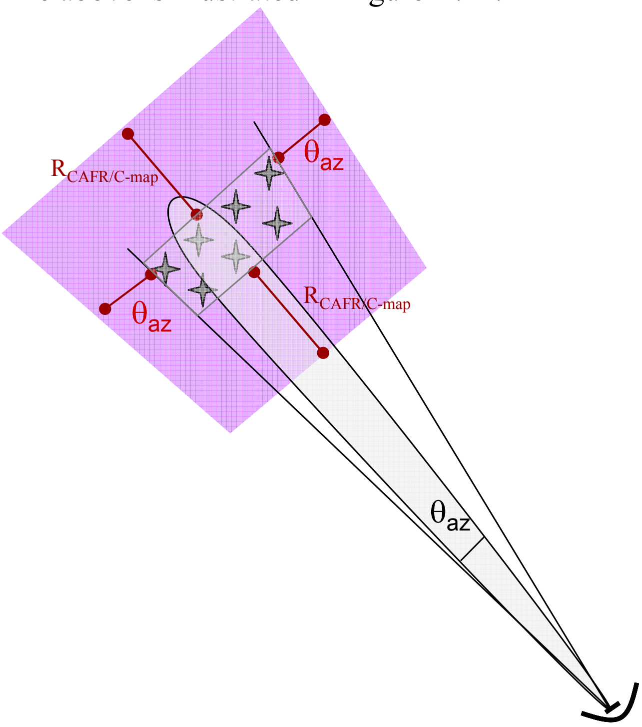


Figure B.4 Area where a windmill park will affect CFAR and cluttermap detection performance

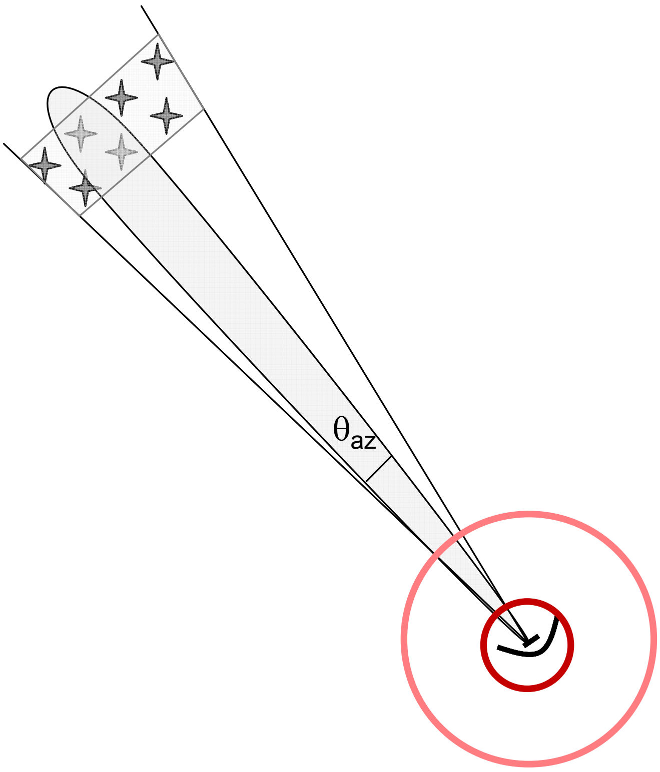


Figure B.5 Ranges where assumption may not be valid

Figure B.5 above shows two range rings around the radar. These are also included in the WTES WF Impact Overview module (section 7.3) to point to the fact that all calculations and discussions in this section assumes far field free space conditions. If the windmills are within the innermost ring (dark red) they are well within the *radar* near field. In that case most of the discussions above are not valid. The exact range to the near field limit is not possible to determine exactly, since the transfer from near filed to far field is continuous. Even so, a reasonable estimate could be that windmills within a range of 1 km off a radar will produce near field effects that are very difficult to estimate in any detail. Windmills should not be placed within this range without very careful evaluation, and preferably on-site experiments using synthetically generated signals to simulate windmill effects.

The outer range ring is there to point to the fact that there is a transition region where the calculations and discussions above are very uncertain, especially in terms of magnitude of the effects the wind park may have. This uncertainty may go in both directions, but at close range between the radar and the wind park (e.g. less than 5 or 10 km) special care should be taken, and other effects than the ones described above may dominate. The quality and fidelity of these calculations do not allow for evaluation of closely separated radar and windmill sites. Again on-site experiments are suggested.

C PRIMARY REFLECTIONS

The strength of the reflected signal is important for the evaluation on the wind turbines influence on the radar (5).

An electromagnetic signal, with an effect P_t sent from an antenna with gain G_t, will at a range of R_t from the transmitter have the power density

$$S_t = P_t G_t \frac{1}{4\pi R_t^2} \qquad (W/m^2) \tag{C.1}$$

When the signal hits an object, the received effect will be scattered in different directions. The transmitted effect is

$$P_\sigma = S_t \sigma \qquad (W) \tag{C.2}$$

when σ is the targets radar cross section.

In the distance R_r from the object the power density of the reradiated effect, P_σ, can be calculated similar to (C.1):

$$S_\sigma = P_\sigma \frac{1}{4\pi R_r^2} \qquad (W/m^2) \tag{C.3}$$

The received signal effect of a receiver antenna with an effective area, A_e, receive this signal, will be

$$P_r = S_\sigma A_e \qquad (W) \tag{C.4}$$

The effective area of the receiver may be expressed by the antenna gain, G_r:

$$A_e = \frac{G_r \lambda^2}{4\pi} \tag{C.5}$$

where λ is the signals wavelength. By combining the equations (C.2), (C.3), (C.4) and (C.5), the effect in the receiver will be

$$P_r = \frac{P_t G_t G_r \lambda^2 \sigma}{(4\pi)^3 R_t^2 R_r^2} \qquad (W) \tag{C.6}$$

To be able to detect the object, with some simplifications, the effect, P_r must satisfaction the following hypothesis:

$$\begin{array}{lll} H_0: & P_r < P_D & \text{object is NOT detected} \\ H_1: & P_r \geq P_D & \text{object is detected} \end{array} \tag{C.7}$$

where P_D is the necessary effect to detect a target.

In the purchase of a monostatic radar system, the minimum detection range, R_0, for a given , σ_0 ,(usually 1 m^2), is often specified. The received effect for monostatic radars is then

$$P_D = \frac{P_t G_t G_r \lambda^2 \sigma_0}{(4\pi)^3 R_0^4} \qquad (W) \tag{C.8}$$

The maximum detection range for monostatic radars is then

$$R = \left(\frac{P_t G_t G_r \lambda^2 \sigma}{(4\pi)^3 P_D} \right)^{1/4} \qquad (m) \tag{C.9}$$

In this equation the radar designer controls all the parameters except the radar cross section σ.

Equation (C.9) can also be used to calculate the radar cross section σ_D that is required for a target to be detected at distance R

$$\sigma_D = \frac{(4\pi)^3 P_D R^4}{P_t G_t G_r \lambda^2} \qquad (\mathrm{m}^2) \tag{C.10}$$

D SECOND REFLECTIONS

The calculations for the Second Reflections are much the same as for the SSR described in section I. The difference is that you calculate the Radar Cross Section (RCS) any possible target must have to be detected as a ghost target when the signal is reflected from a windmill. This is done by

$$\sigma_t = \frac{P_0}{P_t} \frac{(4\pi)^5 R_w{}^4 R_{wt}{}^4}{G_t G_r \lambda^2 \sigma_w} \tag{D.1}$$

This is a variation of the equation (5.2) in (5). P_0 is the signal strength needed at the receiver to detect a target, P_t is the signal strength radiated, R_w is the range from the radar to the windmill, R_{wt} is the range from the windmill to the target, G_t og G_r is the gain at transmitter and receiver respectively, λ is the wavelength and σ_w is the windmill RCS.

Low RCS corresponds to ”worst-case”, and the colour scale is chosen so that red corresponds to a low necessary RCS, while green corresponds to a high necessary RCS. Every pixel in the bitmap will be the lowest necessary RCS value for every windmill.

E SHADOW EFFECT

When an electromagnetic wave is obstructed by an object that has a size comparable with the wavelength, the electromagnetic wave is diffracted and creates a shadow region behind the object. This will be the case when a wind turbine (size of several meters) is obstructing the electromagnetic wave from a radar (wavelength of centimeters to meters).

The wind turbine is modeled as an infinitely long perfectly conducting cylinder with radius r_{cyl}. The incoming (from the radar) electromagnetic primary wave E_z^{prim} is assumed to be a plane wave with electric field component along the z-axis only, and it is also assumed that the electric field is homogeneous in the z-direction. The problem can then be solved in 2 dimensions. The geometry of the problem is shown in Figure E.1.

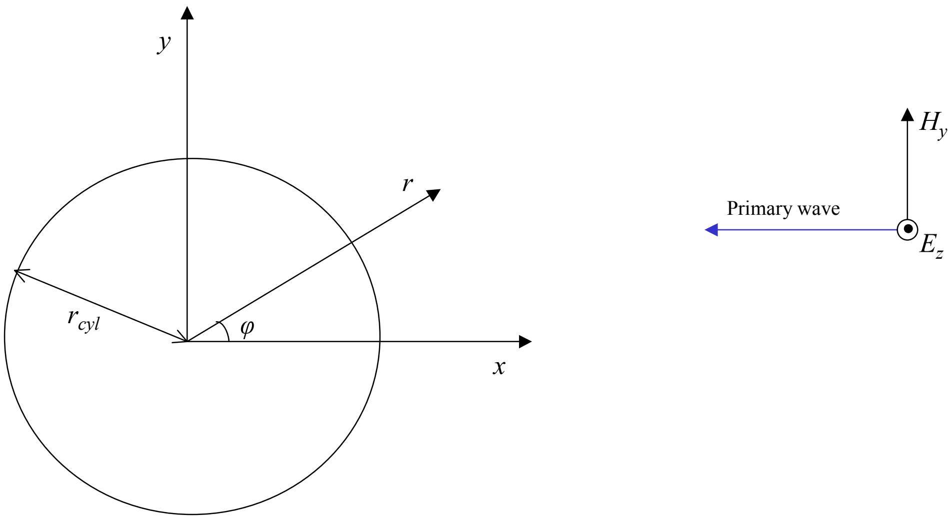


Figure E.1 Diffraction on a conducting cylinder of infinite length (cross-section in the xy-plane).

The total electric field E_z^{tot} around the cylinder (wind turbine) is given by

$$E_z^{tot} = E_z^{prim} + E_z^{\sec} \qquad \text{(E.1)}$$

Here E_z^{prim} is the incoming primary field

$$E_z^{prim} = E_0 e^{jkr\cos\varphi} \qquad \text{(E.2)}$$

where E_0 is the electric field amplitude of the primary wave, r is the distance from the cylinder, φ is the angle around the cylinder, and $k = 2\pi / \lambda$ is the wave number with λ being the wavelength of the primary wave.

$E_z^{\sec}$ is the secondary field generated by the cylinder in response to the incoming field

$$E_z^{\sec} = \sum_{m=0}^{\infty} A_m H_m^{(2)}(kr)\cos(m\varphi) \qquad \text{(E.3)}$$

where $H_m^{(2)}$ are Hankel functions of the second kind, and the coefficients A_m are given by

$$A_0 = -\frac{E_0 J_0(kr_{cyl})}{H_0^{(2)}(kr_{cyl})} \qquad \text{(E.4)}$$

and

$$A_m = -2j^m E_0 \frac{J_m(kr_{cyl})}{H_m^{(2)}(kr_{cyl})} \tag{E.5}$$

The summation in the expression for the secondary field (Equation (E.3)) can be terminated when $m = M$, where M is calculated from

$$M = \text{ceil}\left[10 + 6.4 \cdot \left(\frac{r_{cyl}}{\lambda}\right)\right] \tag{E.6}$$

Equation (E.6) is valid for $r_{cyl} / \lambda \leq 1000$.

For large r_{cyl} / λ, i.e., high frequencies, Equation (E.6) shows that M becomes large and the calculations become time consuming. Equations have been derived in (3) that can be used to quickly calculate the boundary and depth of the shadow region behind the wind turbine. The shadow boundary Y_b (equal to half the width of the shadow) at distance d behind the wind turbine can be calculated from

$$Y_b = \pm \begin{cases} y_b(d), & d > d_0 \\ r_{cyl} + \left(\dfrac{y_b(d_0) - r_{cyl}}{d_0}\right) \cdot d, & d \leq d_0 \end{cases} \tag{E.7}$$

where

$$y_b(d) = \sqrt{\frac{d \cdot r_{cyl}}{w}} \tag{E.8}$$

and

$$d_0 = \begin{cases} 5r_{cyl} \cdot \left(\dfrac{r_{cyl}}{\lambda}\right), & \dfrac{r_{cyl}}{\lambda} > 1 \\ 5r_{cyl}, & \dfrac{r_{cyl}}{\lambda} \leq 1 \end{cases} \tag{E.9}$$

The parameter w is given by

$$w = g \cdot \left(\frac{r_{cyl}}{\lambda}\right)^k \tag{E.10}$$

where g and k are two constants given by

$$\begin{aligned} g &= 1.6 \\ k &= 0.96 \end{aligned} \tag{E.11}$$

The shadow depth is calculated from

$$20\lg E_z^{tot} = a \cdot \left(\frac{d}{r_{cyl}} \right)^{-b} \tag{E.12}$$

where a is given by

$$a = u \cdot \left(\frac{r_{cyl}}{\lambda} \right)^{s} \tag{E.13}$$

and u and s are two constants given by

$$\begin{aligned} u &= -27.714 \\ s &= 0.22298 \end{aligned} \tag{E.14}$$

Finally, the parameter b is given by

$$\lg b = q_3 \cdot \left[\lg\left(r_{cyl} / \lambda \right) \right]^3 + q_2 \cdot \left[\lg\left(r_{cyl} / \lambda \right) \right]^2 + q_1 \cdot \lg\left(r_{cyl} / \lambda \right) + q_0 \tag{E.15}$$

where the coefficients $q_0 - q_3$ have the following values

$\underline{0.1 \leq \frac{r_{cyl}}{\lambda} \leq 10:}$

$$\begin{aligned} q_0 &= -0.2395 \\ q_1 &= -0.02645 \\ q_2 &= -0.01852 \\ q_3 &= -0.003527 \end{aligned} \tag{E.16}$$

and

$\underline{10 < \frac{r_{cyl}}{\lambda} \leq 1000:}$

$$\begin{aligned} q_0 &= -0.2395 \\ q_1 &= 0.01692 \\ q_2 &= -0.08798 \\ q_3 &= 0.02256 \end{aligned} \tag{E.17}$$

The infinitely long conducting cylinder model has one input parameter r_{cyl} that can be adjusted. This gives the model the flexibility to represent wind turbines of different size.

Studies of existing literature (3) indicate that the cylinder radius should be set equal to the maximum tower radius (at the base of the tower). The shadow effects on wind turbines are discussed in more detail in (3).

The shadow effects on windmills are discussed in more detail in (3).

F RADAR CROSS SECTION (RCS)

Two windmill models are chosen for simulation, as seen in Table F.1.

Navn	Tower			Nacelle options				Rotor options			
modell	**t-rad**	**b-rad**	**h**	**rad**	**off-a**	**l**	**h-l**	**b-l**	**con-a**	**blad-a**	**f**
90m	1	2	90	2	3	8	4	50	0	0	10
120m	1.5	2.5	120	2.5	3	10	5	65	0	0	10

Table F.1 Parameters for the two generic windmill models.

The different parameters in Table F.1 are:

- Tower
  - t-rad tower, top radius
  - b-rad tower, bottom radius
  - h tower, height
- Nacelle options
  - rad nacelle, radius (round structure)
  - off-a nacelle, offset angle
  - l nacelle, length
  - h-l nacelle, spindle (hub) length
- Rotor options
  - b-l rotor, wing blade length
  - con-a rotor, wing conicity angle
  - blad-a rotor, wing angle (rotation angle)
- f maximal frequency in GHz the model is generated for

The simulations and the theory will be described in a separate report (4).

G ADVANCED PROPAGATION MODEL (APM)

APM - Advanced propagation model, is a program calculating how electromagnetic radiation propagates. WTES uses the program to find how the intensity of the radar beam changes when propagated in the terrain. APM is American free software, verified through many years of use (6).

In a RHI plot – Range Height Indicator – you use a coordinate system where the x-axis follows the earth. The height above ground is given at the y-axis and the range is given along the curved x-axis. The values of the signal attenuation (dB), is converted to a colour scale shown in the legend.

The propagation is calculated only due to the terrain and not the wind turbine. The wind turbines are just drawn onto the calculated picture.

H ELECTRONIC WARFARE (EW)

Jamming is a problem to military radars, and the problem may be even worse in the vicinity or wind turbines, as shown in Figure H.11.

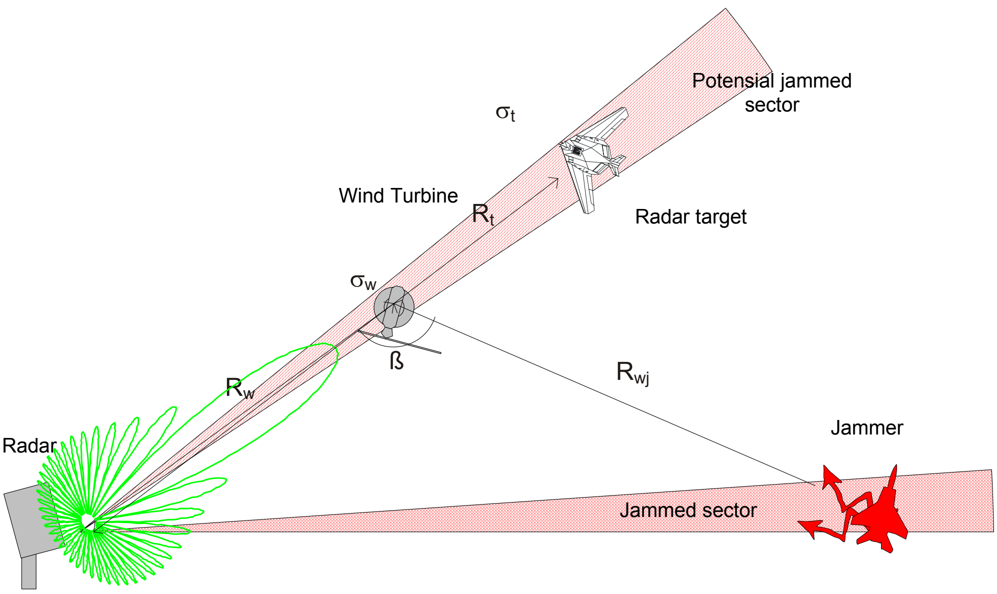


Figure H.1 The principle of considering a possible new jammed sector due to reflections by a wind turbine.

According to the calculations in chapter C, the received effect from the target can be calculated by

$$P_{rt} = P_t G_t \frac{1}{4\pi R_t^2} \sigma_t \frac{1}{4\pi R_t^2} A_r = \frac{P_t G_t G_r \lambda^2 \sigma_t}{(4\pi)^3 R_t^4} \qquad \text{(H.1)}$$

Received effect from the jamming source will be

$$P_{rj} = P_j G_j \frac{1}{4\pi R_{wj}^2} \sigma_w \frac{1}{4\pi R_w^2} A_r = \frac{P_j G_j G_r \lambda^2 \sigma_w}{(4\pi)^3 R_w^2 R_{wj}^2} \tag{H.2}$$

Detecting the target, requires that

$$P_{rt} > DP_{rj} \tag{H.3}$$

Here D is the detection threshold.

Combining these equations gives a false jammed sector in the direction of the wind turbine(s) if the distance from the jamming source to the wind turbine is

$$R_{wj} < \frac{R_t^2}{R_{wr}} \sqrt{\frac{DP_j G_j \sigma_w}{P_t G_t \sigma_t}} \tag{H.4}$$

I SECONDARY SURVEILLANCE RADAR (SSR)

The Signal Level for a signal reflected from one or more windmills in a certain height is calculated with a given resolution. After generating a pixmap for each windmill, they are set together choosing the highest value in every pixel. The pixel values are translated into colours from green to red, via yellow. Green represents the lowest signal level and red the highest.

I.1 Signal Strength

The Signal strength is calculated using

$$P_r = \frac{P_t G_t G_r \sigma_w \lambda^2}{(4\pi)^2 R_1^{\,2} R_2^{\,2} L_{atm}} \tag{I.1}$$

P_r is received effect in Watt, P_t is radiated effect, G_t and G_r is gain of transmitted and received effect respectively, σ_w is the windmills radar cross section (RCS), λ is the wavelength, R_1 is the range between the radar and the windmill, R_2 is the range between the windmill and the target, and L_{atm} is the atmospheric attenuation.

I.2 Radar Cross Section (RCS)

For bistatic scattering the differential radar cross section is calculated by

$$\sigma(\overline{\beta}, \varepsilon, \tau) = k_0 l^2 r \cos\left(\frac{\overline{\beta}}{2}\right) \frac{\cos^2(\tau - \alpha)}{\cos(\varepsilon - \alpha)} \left[\frac{\sin(k_0 l\{\sin(\varepsilon - \alpha) + \sin(\tau - \alpha)\})}{k_0 l\{\sin(\varepsilon - \alpha) + \sin(\tau - \alpha)\}}\right]^2 \tag{I.2}$$

where $\overline{\beta}$ is the bistatic angle projected down on the horizon plane, ε is the angle between angle of incidence and the horizon plane, τ is the angle between angle of departure and the horizon plane, k_0 is the wave number, l is the height of the windmill tower, r is the mean radius of the windmill tower and α is the conicity angle of the tower.

When having forward scattering ($\overline{\beta}$=180°) you must use

$$\sigma(\varepsilon,\tau)=0 \tag{I.3}$$

The near field of the windmill is defined by

$$R \geq \frac{2D^2}{\lambda} \tag{I.4}$$

where D is the objects largest relevant dimension, (the tower height is used). If the radar and/or target are within this distance, the tower is divided into smaller pieces, which separately fulfil equation (I.). The differential radar cross section will then be

$$\sigma_w = \left| \sum_{n=1}^{N} \sqrt{\sigma_n} e^{ik_0 (r_n^i + r_n^o)} \right|^2 \tag{I.5}$$

where r_n^i og r_n^o is the distance between radar and windmill and windmill and target respectively. The equations are found in (2) and (5).

J RADIO LINK

The exclusion zones for the radio link are calculated separately for the near field and the diffraction part and the summarized. The two calculations are described below.

J.1 Near Field Range

A Near Field Range (in meters) is calculated around each antenna. The radius of this circle is

$$D_{nf} = \frac{N_{nf} \eta D_a^{\ 2}}{\lambda^2} \tag{J.1}$$

N_{nf}	Conservative constant (primary set to 3)
η	The antenna efficiency (a number between 0 and 1, set in "settings")
D_a	The antenna physical aperture diameter (set in "settings")
λ	Wavelength (set in "settings", as frequency)

For antenna with out a recognisable physical aperture, the equation below is used

$$D_{nf} = \frac{N_{nf} \lambda g}{\pi^2} \tag{J.2}$$

where g is the antenna larger linear gain (usually right ahead).

J.2 Diffraction

To avoid diffraction effects an exclusion zone called a Fresnel zone is defined. The n'th Fresnel zone is defined to include all points that fulfils

$$d_{rp} - d_{sw} = n\frac{\lambda}{2} \tag{J.3}$$

d_{rp}	Distance of signal reflected in the point on the way between two antennas
d_{ws}	Distance of signal directly between two antennas
λ	Wavelength

It is chosen to use the whole 2nd Fresnel zone as an exclusion zone.

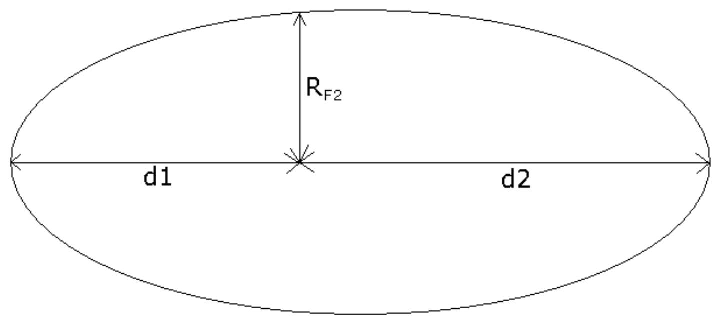


Figure J.3 Approximation to the 2nd Fresnel zone.

A sufficient approximation of the distance from the centre line to the end of the exclusion zone is given by

$$R_{F2} = \sqrt{\frac{2\lambda d_1 d_2}{d_1 + d_2}} \tag{J.4}$$

R_{F2} is the radius for the ellipsoid along the centre line, d_1 and d_2 is the distance to each of the antennas.

The definition of a Fresnel zone gives an ellipsoid with an antenna in each focus. The approximation will the fail near the antennas, but this is accounted for in the near field rage calculations (section J.1).

J.3 Reflection or scattering

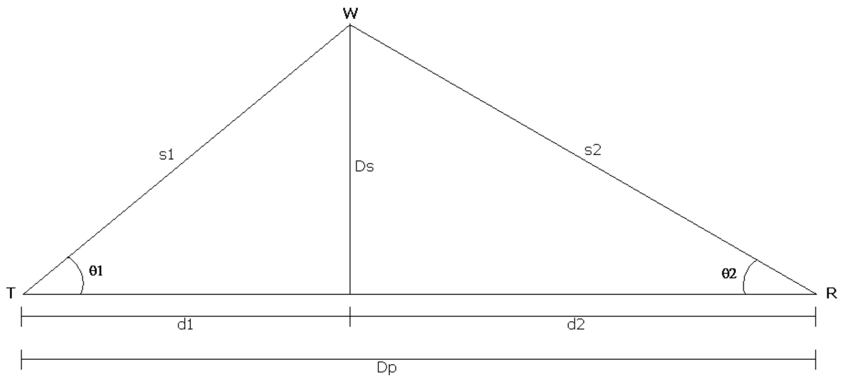


Figure J.2 Reflection or scattering.

In the reflection or scattering zone the signal to noise ratio is below a threshold. The signal is the direct path between T and R, while noise is the path T-W-R. W is the windmill reflecting the signal. The ratio is given by the equation

$$r_{ci} = \frac{4\pi s_1^{\,2} s_2^{\,2} g_1(0) g_2(0)}{\sigma D_p^{\,2} g_1(\theta_1) g_2(\theta_2)} \tag{J.5}$$

$g_i(\theta_i)$ is the antenna gain as a function of the angle θ_i (i=1,2). The reflection zone is then dependent of the antenna radiation pattern. In the calculations the functions g_i is chosen to be a non-normalized Gauss function, $N(x,\mu,\sigma)$, with a standard deviation $\sigma = 0.07$ radians and a mean value $\mu = 0$.

$$N(x,\mu,\sigma) = e^{-\frac{(x-\mu)^2}{2\sigma^2}} \tag{J.6}$$

The reflection zone is then drawn iterative until the desired ratio rci is achieved. This is done for every point between the two antennas.

K PASSIVE SENSOR

The calculations for the Passive Sensor are restricted to the radar frequencies where the radar equation is valid. The signal strength received at the passive sensor is calculated by the equation

$$P_r = \frac{P_t G_t G_r \sigma_w \lambda^2}{(4\pi)^2 R_1^{\,2} R_2^{\,2} L_{atm}} \tag{K.1}$$

P_r is received effect in Watt, P_t is radiated effect by the emitter, G_t and G_r is gain of transmitted and received effect respectively, σ_w is the windmills radar cross section (RCS), λ is the wavelength, R_1 is the range between the emitter and the windmill, R_2 is the range between the windmill and the passive sensor, and L_{atm} is the atmospheric attenuation.

L HIGH FREQUENCY (HF)

The HF calculations are described in (7) and (8). The Ground conductivity map of Norway is given in Figure L.1 and in (10).

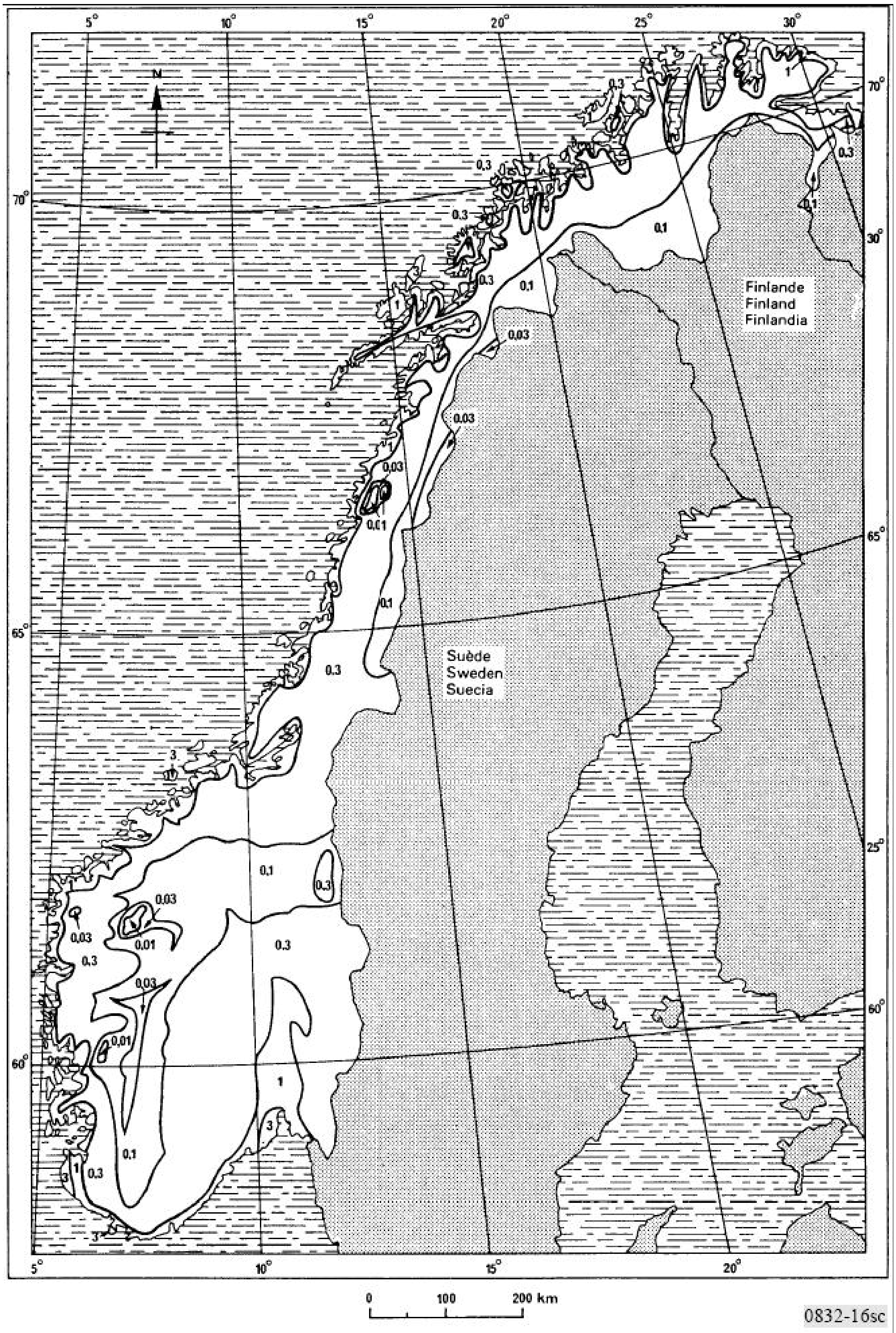


Figure L.1 *Ground conductivity map of Norway, from (10). Numbers are given in units of mS/m.*