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TNO report

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Radar Interference Study. A Proposal for New Regulation Guidelines

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Summary

In the Netherlands, Agentschap Telecom (AT) is responsible for issuing frequency management and enforcement. The agency is confronted with an increasing number of requests for radar systems for various applications, making the issuing process more difficult. In addition, there are modern radar systems that use a relatively wide frequency band. This requires an adjustment of the regulations.

AT has issued a study to reveal the interference potential and to propose measures to mitigate interference. To structure the analysis, AT has issued a set of research questions. The study is limited to the S- and X- radar bands.

The study has taken pulse radar, pulse compression radar and FMCW radar into account, these are the types currently deployed. For each radar type, the sensitivity for interference from each of the three types has been determined. This interference is depending on the used transmit signal, antennae, the radar processing, radar-to-radar distance and environment. Radars employ techniques to mitigate radar-to-radar interference, the most used techniques have been studied and analysed for their applicability and effectiveness.

The interference level is calculated for a number of “typical” radars that can be considered model for the majority of radars currently present in the Netherlands, as well as for many future radars. The interference level is calculated taking into account the effect of mitigation techniques employed on interfering and on interfered radar. Based on this analysis, a number of guidelines have been drawn up to avoid interference.

The study has compared the situation with respect to interference with that of Belgium and Germany. Especially Germany already has taken a number of measures that are proposed in this study for the Dutch situation.

The study results allowed the research questions to be answered. Moreover conclusions and recommendations are postulated. The conclusions provide a concise view on the current interference landscape. The recommendations contain the proposed guidelines to Agentschap Telecom.

Samenvatting

In Nederland is Agentschap Telecom (AT) verantwoordelijk voor frequentiemanagement en handhaving. Het bureau wordt geconfronteerd met een toenemend aantal aanvragen voor radarsystemen voor verschillende toepassingen, waardoor het uitgifteproces moeilijker wordt. Daarnaast zijn er moderne radarsystemen die een relatief brede frequentieband gebruiken. Dit vereist een aanpassing van de regelgeving.

AT heeft deze studie laten uitvoeren om het interferentiepotentieel in kaart te brengen en maatregelen voor te stellen om interferentie te verminderen. Om de analyse te structureren heeft AT een aantal onderzoeksvragen opgesteld. Het onderzoek is beperkt tot de S- en X-radarbanden.

In het onderzoek is rekening gehouden met pulsradar, pulscompressieradar en FMCW-radar, dit zijn de typen die momenteel worden gebbruikt. Voor elk radartype is de gevoeligheid bepaald voor storing van ieder van de drie radartypen. Deze storing is afhankelijk van het gebruikte zendsignaal, antennes, de radar signaalverwerking, de afstand van radar tot radar afstand en de omgeving. Radars maken gebruik van technieken om radar-naar-radar-interferentie te verminderen, de meest gebruikte technieken zijn bestudeerd en geanalyseerd op hun toepasbaarheid en effectiviteit.

Het interferentieniveau wordt berekend voor een aantal "typische" radars die model staan voor de meeste radars die momenteel in Nederland in gebruik zijn, maar ook voor veel toekomstige radars. Bij het berekende interferentieniveau is rekening gehouden met het effect van de mitigatietechnieken die op de storende en op gestoorde radar worden gebruikt. Op basis van deze analyse is een aantal richtlijnen opgesteld om interferentie te voorkomen.

De studie heeft de situatie op het gebied van interferentie vergeleken met die van België en Duitsland. Vooral Duitsland heeft al een aantal maatregelen genomen die in dit onderzoek worden voorgesteld voor de Nederlandse situatie.

Op basis van de onderzoeksresultaten konden de onderzoeksvragen worden beantwoord. Bovendien zijn conclusies en aanbevelingen opgesteld. De conclusies geven een beknopt beeld van de huidige interferentie situatie. De aanbevelingen bevatten de voorgestelde richtlijnen aan Agentschap Telecom.

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Appendices

1 Introduction

1.1 Background

In the Netherlands, Agentschap Telecom (AT, Dutch for: Radiocommunications Agency) is responsible (among other things) for issuing frequency management and enforcement. The agency is confronted with an increasing number of requests for radar systems for various applications, such as for the observation of ships, birds, drones, aircraft and for activating obstruction lights, etc. As a result, more and more requests are made for frequencies in the frequency range intended for these radars, what makes the issuing process more difficult. In addition, there are modern radar systems that use a relatively wide frequency band. This requires an adjustment of the regulations. As one of the framework contractors for research and advisory services, Dialogic has been asked by AT to research the modernisation of the issuing process. Dialogic has asked TNO to support her in this, given her expertise in this area. The report has been a combined effort between TNO and Dialogic. TNO has written the chapters 1 to 5 and Dialogic Chapter 6.

1.2 Research questions

The following questions have been postulated by AT:

1. Is there a general need to adhere to planning criteria when granting a license for a radar system?
   a. If not, what is the (preferably also numerical) substantiation for this? See also under point b.
   b. If so, what are these planning criteria, taking into account the performance criteria of the different radar systems? Given that parameters such as central frequency, bandwidth, transmission power (in EIRP), modulation shape, antenna height, antenna direction and location are determined.
   c. What are the desired / required performance criteria of radars in this respect and can these be translated into concrete protection criteria that must be incorporated in the radio planning and that are reflected in the aforementioned parameters?
2. Is there a generic standard or value to be applied or a substantiated rule of thumb?
3. If this is possible and useful, what are the (planning) criteria to be applied per category?
4. What are the developments with regard to radar applications and systems and what consequences can this have for radio planning and the possible exclusion or facilitation of new and certain types of radar systems?
5. How do other European countries deal with the radio planning of radars? Emphasis is placed on the neighbouring countries Germany and Belgium, taking into account the possibly required notification and coordination of frequency use between countries.

1.3 Related frequency band

The assignment of AT only covers radar usage in the S- and X-band frequency range. The frequency allocations for these bands are given in Table 1.1 (ignoring ranges solely in use for military radar).

Table 1.1 Frequency allocation in S-band and X-band, from Nationaal Frequentieplan 2014 [1].

Band	Frequency (MHz)	Allocation
S-band 2700-3300 MHz	2700 - 2900	Air Traffic Control (ground based radar)
	2900 - 3100	Maritime radar, land based as well ship borne
	3100 - 3400	Radar
X-band 8750 – 9500 MHz	8500 - 8750	Radar
	8750 - 8850	Air traffic control radar, airborne
	8850 - 9000	Maritime radar, (fixed) radar for maritime traffic control
	9000 - 9200	Air traffic control radar Maritime radar, (fixed) radar for maritime traffic control
	9200 - 9300	Radar
	9300 - 9500	Maritime radar Airborne weather radar

1.4 Approach

To answer the questions asked by AT, the interference potential of radars to each other is analysed in a number of steps, each of which is described in a separate section.

In Chapter 2, the three main classes of relevant radars, being pulse radar, pulse compression radar and FMCW radars, are investigated and their respective operation and signals are analysed.

In Chapter 3, the interference mechanisms are investigated, starting from the transmitted radar signals and taking into account the major factors that govern the interference mechanisms: the mutual coupling, the mutual sensitivity and the distance. Linked to the interference mechanisms are the mitigation techniques that are also analysed.

In Chapter 4, the actual analysis is performed for the various ways radars interfere each other. The analysis is performed based on a number of typical radars, that by their parameters by and large stand for the majority of radars used.

In Chapter 5, the insights of the international comparison are presented. This chapter has been written by Dialogic.

Chapter 6 provides detailed answers, based on the analysis performed in Chapter 4, to the research questions postulated by AT.

The conclusions and recommendations are given in Chapter 7. Abbreviations are explained in Chapter 8, while references are listed in Chapter 9.

Finally Chapter 10 provides the signature of the report by relevant TNO and Dialogic employees.

2 Radar types

The study recognizes three basic radar types:

- Pulse radar,
- Pulse compression radar,
- FMCW radar.

In this chapter the basics of each type are explained as well as the radar signals they use.

A radar transmits a signal that travels from the radar to a target. At the target the signal partially reflects back to the radar. The radar receives this signal and determines the time it took from transmission to reception, see also Figure 2-1.

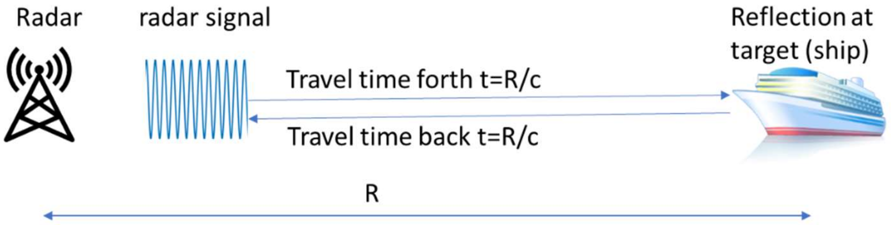

Figure 2-1 Radar basic operation.

The radar signal travels at the speed of light, *c*, which is about 300,000 km/s. The distance *R* will result in a travel time of:

$$t = 2R/c$$

The factor 2 takes into account the signal has to travel back and forth.

The amount of energy received by the radar receiver is given by the radar equation for free space and no loss conditions:

$$\mathrm{P_r} = \frac{\mathrm{P_t G^2 \lambda^2 \sigma}}{(4\pi)^3 \mathrm{R}^4}$$

where:
P_r is received power [W]
P_t is transmitted power [W]
G is antenna gain
λ is wavelength of the radar signal [m]
σ is radar cross section (RCS) [m^2]
R is range (or distance) [m].

The wavelength relates to the transmitter frequency as:

$$\lambda = {}^{c}/_{F_t}$$

where F_t is transmit frequency [Hz].

2.1 Pulse radar

The common way of measuring *t* in the early days of radar was the use of a short radar pulse, see Figure 2-2. The radar measures the time it takes the pulse to travel forth and back:

$$R = \frac{t * c}{2}$$

The radar repeats the pulse transmission every PRI (pulse repetition interval) seconds, or the pulse is repeated PRF (pulse repetition frequency) times per second, PRI=1/PRF. The pulse itself has a duration of t_p seconds.

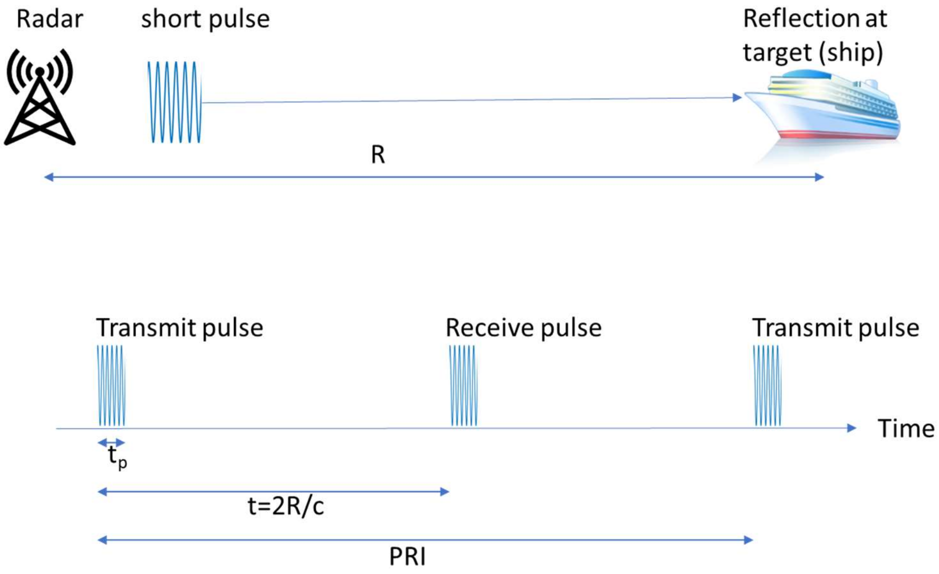

Figure 2-2 (short) pulse radar.

The maximum range of the radar R_{max} = PRI * c / 2. The resolution of the radar is t_p sec, which equals a length of $l_p = t_p * c$. Typical values are:

- PRF between 250 Hz and 5 kHz, this equals to a PRI between 4 ms and 200 µs. The resulting maximum ranges are 600 km and 30 km.
- Pulse duration t_p between 100 ns and 10 µs, equalling pulse lengths and hence a resolution of 15 and 1500 meter.

A generic lay-out of a pulse radar is given in Figure 2-3. The transmitter commonly is a magnetron. The pulses are not modulated, due to the finite length the pulse has a given bandwidth, notwithstanding the fact a “single frequency” is transmitted.

$$B = {}^{1}/_{t_p}$$

where t_p is the pulse length [s] and *B* the resulting bandwidth [Hz].

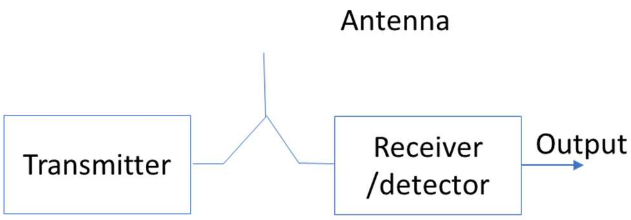

Figure 2-3 Generic layout of pulse radar.

To receive the pulse, the receiver needs to have at least the same bandwidth *B*.

2.2 Pulse compression radar

Magnetron transmitters are capable of transmitting short pulses at high peak powers. Modern Solid State transmitter are capable to transmit less peak power but at higher duty cycles, thus longer radar pulses. The reason for longer radar pulses is the fact that they contain more energy and thereby increase the sensitivity of the radar, at the expense of a lower resolution. Pulse compression allows the use of longer pulses without sacrificing resolution.

In a radar with pulse compression, a modulated pulse is used, as is shown in Figure 2-4. The radar compares the transmitted pulse with the received pulse, and determines the moment they are aligned, see Figure 2-5. The pulse compression even works with overlapping long pulses, as is shown in Figure 2-6, where the radar receives reflections of three targets, at 40, 70 and 75 km. The pulse length is 66 µs or 10 km.

The ratio between the long pulse and the compressed short pulse is called the pulse compression ratio (PCR).

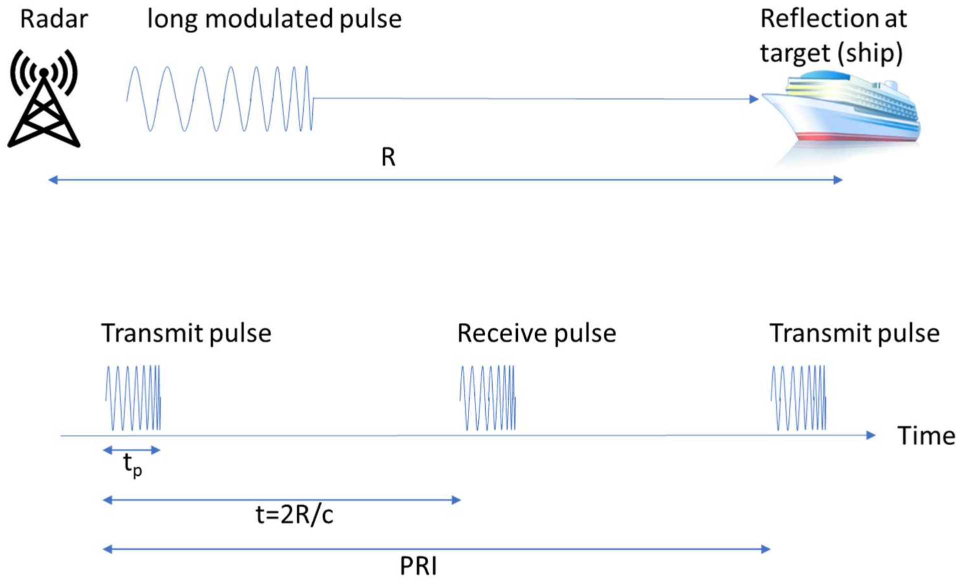

Figure 2-4 Pulse compressor radar.

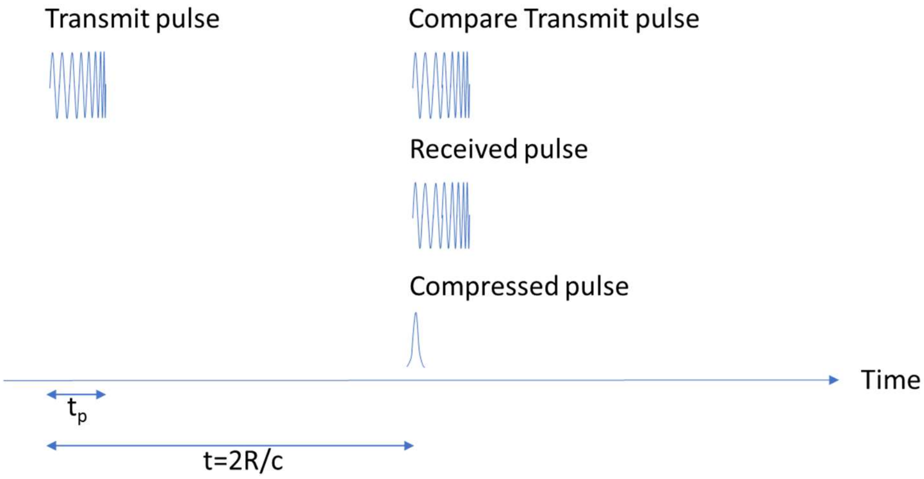

Figure 2-5 Pulse compression operation.

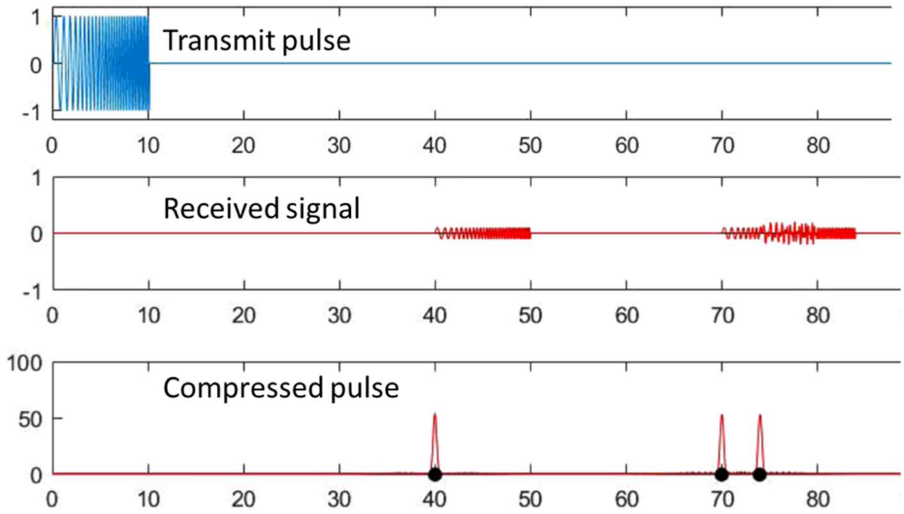

Figure 2-6 Pulse compression with overlapping receive signals.

Pulse compression radars use long and modulated radar pulses. As indicated earlier, pulse compression is most commonly used by modern solid state radars. By transmitting relatively long pulses, they can reduce the transmitter power while maintaining the same average power (e.g. a short pulse of 10 kW in 100 ns emits the same energy as a 100 W pulse of 10 µs).

To achieve the same resolution as with a short pulse, long radar pulses are modulated, most commonly a frequency sweep is used. Due to the modulation, the bandwidth of the transmitted signal increases. As an example, to achieve the same resolution as with the short pulse of 100 ns, the bandwidth of the long pulse also has to be 10 MHz. Also the receiver needs to have a bandwidth of 10 MHz.

During the pulse transmission the receiver cannot receive any signals. In case of transmitting large pulse (e.g. 100 µs), the radar will not be able to receive any echo’s from nearby objects (15 km for 100 µs). This is known as the blind distance. To overcome this effect, radar manufacturers often apply multiple interlaced pulse trains with short pulses for short range detection and long pulses for long ranges detection. Sometimes even an intermediate pulse width is applied for distances in between. To separate the various pulse trains, they each have different frequencies This implies that these radars utilise more instantaneous bandwidth, For example, if the bandwidth of the pulse is 10 MHz, then a radar using a short and a long pulse will occupy at least 20 MHz. With an intermediate pulse added, this will raise to 30 MHz. Note however that a typical magnetron navigation radar uses up to 60 MHz due to magnetron frequency variations.

A generic lay-out for a radar using long pulses is given in Figure 2-7. The received pulse is undergoing a process called pulse compression. The pulse compressor uses the modulation of the pulse to calculate the corresponding short output pulse.

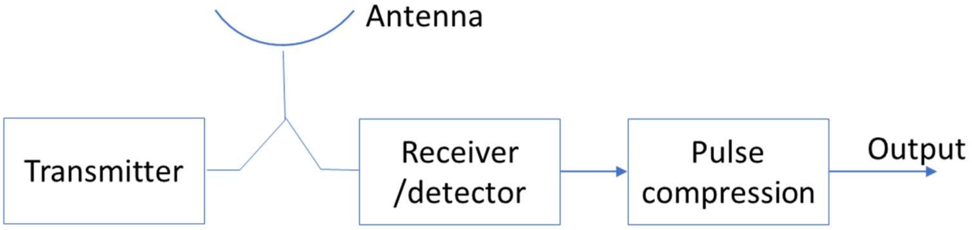

Figure 2-7 Generic lay-out of pulse compression radar.

2.3 Continuous wave radar

Continuous Wave (CW) radars use frequency modulation (FM), hence the name FMCW radar. They measure the travel time of the transmitted signal by comparing where the received signal is in the modulation sequence, as opposed to the transmit signal.

The concept is explained in Figure 2-8. FMCW radars almost exclusively use a linear frequency sweep as modulation, as is shown in the figure. Also here, *t=2R/c*. Note the fact that FMCW radars do transmit while they receive.

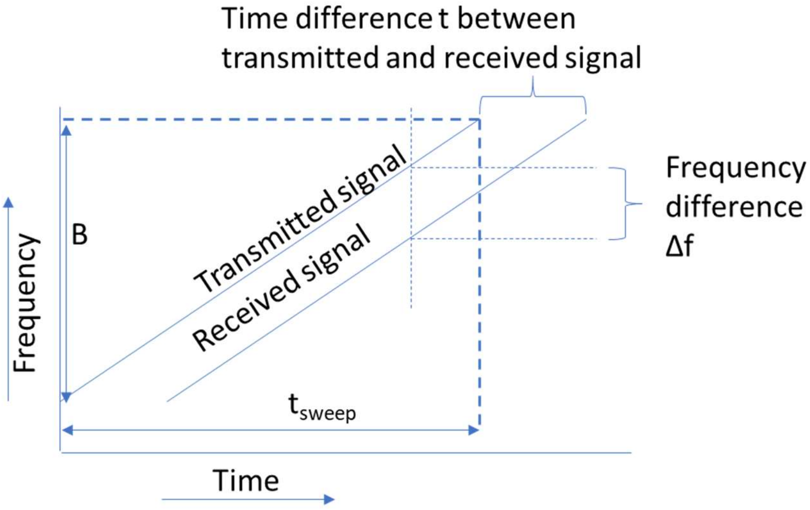

Figure 2-8 Linear frequency sweep in FMCW radar.

As for pulse radar, there is a time difference between the transmitted signal and the received signal, this time difference corresponds to the distance of the target. As can be seen in Figure 2-8, the time difference results in a frequency difference. The frequency difference is measured by the detector. The range is calculated as:

$$R = \frac{\Delta f * t_{sweep} * c}{2B}$$

where:
R is the distance to the target [m]
Δf is the frequency difference between transmitted and received signal [Hz]
B is the sweep bandwidth [Hz]
t_{sweep} is the time to sweep the full sweep bandwidth B [s]
c is the speed of light [m/s].

The maximum range R_{max} of the FMCW radar corresponds to a maximum frequency difference:

$$f_{max} = \frac{R_{max} * 2 * B}{t_{sweep} * c}$$

FMCW radars usually have a filter suppressing frequency differences above f_{max}.

For virtually all FMCW radars, $f_{max} << B$. The theoretical maximum range would be for $f_{max} = B$, or:

$$R_{th,max} = \frac{t_{sweep} * c}{2}$$

where $R_{th.max}$ is the theoretical maximum range [m].

The maximum range R_{max} is hence determined by the processing having a filter cut-off at f_{max}. The filter largely contributes to the FMCW radar suppression of signals from interfering radars.

The generic lay-out for a radar is given in Figure 2-9, and shows the detector (frequency difference output), the filter and the frequency analyser (converting frequency to distance).

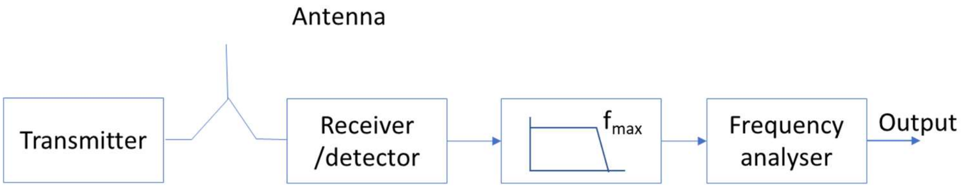

Figure 2-9 Generic lay-out FMCW radar.

As an example:
The FMCW radar uses 10 MHz bandwidth and has a sweep time of 5 ms. The maximum range is 1 km. If we measure a frequency difference of 10 kHz, this implies the distance is 750 m. The maximum frequency difference is 13.3 kHz.

Note that FMCW radars usually have short detection ranges, in the order of kilometres. As a consequence, FMCW frequency differences usually are in the audio range, for which processing is easy. Many components (AD converters, processing) are easily available. Range measurement merely requires a frequency analyser for audio frequencies.

Raymarine, Lowrance, Simrad, B&G[1] all have similar FMCW radar systems. For one of them the relevant specifications are given in Table 2.1, showing typical characteristics obtained from Reference [2] and Reference [3].

Table 2.1 Typical FMCW characteristics.

Antenna Beam Width Horizontal	5.2°+/-10% (-3dB width)
Antenna Beam Width Vertical	25°+/-20% (-3dB width) °
Transmitter Frequency	X-band - 9.3 to 9.4Ghz
Transmitter Power Output	(at antenna port) 100mW nominal
Sweep bandwidth B	75 MHz max.
Sweep repetition frequency (f_{sweep})	200 Hz
Side lobe level	-25 dB (outside 10°)

Given the antenna dimensions and frequency, the antenna gain can be estimated at 24 dBi.

2.4 Frequency diversity

In itself, frequency diversty is not a “radar type”. Each of the radar types (pulse, pulse compression and CW) could apply frequency diversity.

Frequency diversity is the use of multiple transmit frequencies. Already in the “magnetron age”, this technique was applied by using two magnetrons (and two transmitters) at two different frequencies. In the “digital age” frequency diversity can easy be accommodated and it is easy to change between the various frequencies. There are many reasons to apply frequency diversity, among them:
- Clutter reduction
- Multipath reduction
- Detection improvement

The improvement achieved by frequency diversity is usually increasing with increasing frequency difference between the transmit frequencies.

In modern radar the frequency is adaptable, in classic magnetron radar one needs to buy separate magnetrons for each appropriate frequency. Thereby, frequencies can be adjusted to be in accordance with the regulations as presented in Table 1.1.

In section 2.2 we had the example of the radar transmitting both short and long pulses and using 20 MHz of bandwidth, if frequency diversity (for example two frequencies) is applied this would require at least 40 MHz, but it could for example also be 100 MHz, see Figure 2-10. Note that a large separation implies some of the

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[1] Lowrance, Simrad, B&G co-operate on their models.

intermediate bandwidth is unused. If this intermediate band is large enough, it can accommodate transmissions of other nearby radars.

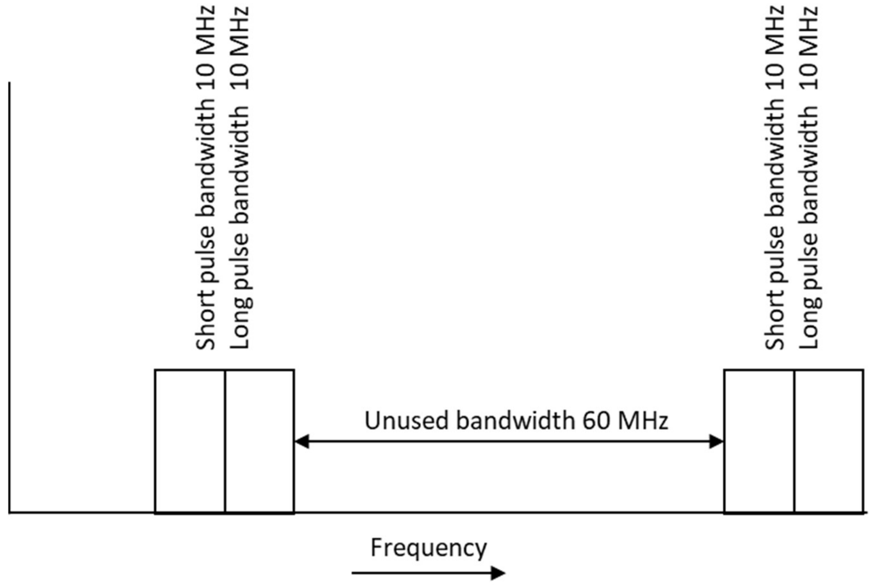

Figure 2-10 frequency diversity

3 Interference mechanisms

For radar to radar interference there are three major governing factors:

- The mutual coupling.
- The mutual sensitivity for each other's transmitter signals. This depends on the used transmit signal and the related signal processing.
- The distance.

These mechanisms are described in the sections that follow.

3.1 Radar signals

We distinguish three types of radar signals used:

- Short radar pulses
  These pulses are commonly used by "classic" magnetron radars and do not have modulation.
- Long radar pulses
  These pulses are commonly used by modern (often solid state) radars and are modulated.
- Continuous wave
  These signals are often used by small relatively cheap radars and are modulated, usually with a linear frequency sweep.
  (Radars using unmodulated continuous wave transmit signals do exist, however not in the considered frequency bands.)

3.1.1 Short radar pulses

Short radar pulses are the domain of the pulse radar as described in Section 2.1. The short pulses are not modulated and the pulse has a given bandwidth:

$$B = {}^{1}\!/_{t_p}$$

The receiver has at least the same bandwidth and hence is sensitive to all signals within this bandwidth. As an example, a pulse length of 100 ns results in a bandwidth of 10 MHz.

Many pulse radars use a magnetron for signal generation. Magnetron frequencies vary from device to device, moreover they vary with age. Deviations can be up to 30 MHz.

3.1.2 Long radar pulses

Long radar pulses are the domain of the pulse compression radar. The long pulses are modulated and this results in a bandwidth *B* as discussed in Section 2.2. The receiver bandwidth needs to be equal to *B*, to capture the full modulation of the radar pulse.

The receiver is sensitive to any signal within its bandwidth, however any foreign signal[2] "decorrelates" (the mathematical way of saying "cannot be compressed") in the pulse compressor.

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[2] Even signals of other pulse compression radars, if they use different modulation.

3.1.3 *Continuous wave transmit signal*

FMCW radar as described in Section 2.3 is the domain of modern solid state marine radars. They in general use large sweep bandwidths and the FMCW signal changes linear over the sweep time t_{sweep}.

The FMCW radar receives all signals within its bandwidth B, however a filter is applied cutting off frequencies beyond f_{max}. Given that $f_{max} << B$, most of the signals received within the band B are suppressed.

3.1.4 *Transmitted power*

The transmitter power for radars depends on the used transmit signals. In Table 3.1 the relative power levels (signal level compared to the radar using short pulses) are given for radars using the various signals, assuming all three have equal performance. Note that for all the transmit signals the average power is equal.

Table 3.1 Relative transmit power.

Transmit signal	Relative power level (order of magnitude)
Short pulse	1
Long pulse	1/PCR
CW	t_p/PRI (Pulse length t_p and Pulse Repetition Interval of the short pulse signal)

Note that the values are given for radars with equal performance, so equal range. FMCW radars however usually have short ranges.

3.1.5 *Naming*

Radars using long modulated pulses are referred to as pulse compression radars.

Radars using FMCW signals are commonly referred to as “Broadband radars”, especially in the maritime (yachting) domain, where these radars tend to become ubiquitous.

Radars transmitting signals that interfere other radars are referred to as “interfering radar” or “source radar”.
Radars interfered by signals from other radars are referred to as “interfered radar” or “victim radar”.

3.2 Coupling mechanism

In order to cause interference, the signal of the interfering radar has to reach the radar that is interfered. In this section we explain the relevant mechanisms and parameters.

The basis for this process is the radio equation, for free space and lossless condition:

$$P_R = \frac{P_T G_T G_R \lambda^2}{(4\pi R)^2}$$

where:
P_R is received power [W]

P_T is transmitted power [W]
G_T is transmit antenna gain
G_R is receive antenna gain
λ is wavelength [m]
R is Range, the distance between transmit and receive antenna [m].

Both radio and radar equation look similar. Main difference between the radio and radar equation is the influence of distance. The radio equation is inversely proportional to R^2. In the radar equation, the radar signal has to travel to the target (and is attenuated inversely proportional to R^2), is “retransmitted”(reflected) by the target and is attenuated again inversely proportional to R^2, resulting in an overall attenuation inversely proportional to R^4.

This equation is used to determine the amount of power that is received by the victim radar, due to the signal transmitted by the source radar. It is clear that the amount of interference is determined by the antenna gain and the distance.

Radars do have directional antennas to transmit the energy as much as possible in a single direction, thereby increasing their maximum range. This focusing of energy towards a given direction creates antenna gain. As a consequence of the focusing process, those antennas only emit lower levels in other directions. The higher the gain, the narrower the beam has to be. Additionally, many radars employ the narrow beam of the antenna to achieve angular resolution.

A typical antenna diagram is given in Figure 3-1. The gain is high in the main lobe, this main lobe is specified by its beam width and its gain as referred to an omni-directional (isotropic) antenna (having equal gain in all directions). Some radiation also is present in other directions, especially at the back (although certain antenna types, especially slotted waveguide antennas, virtually do not have a back lobe).

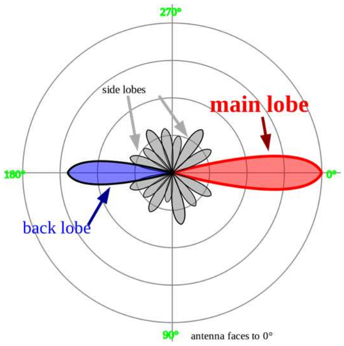


Figure 3-1 Antenna diagram.

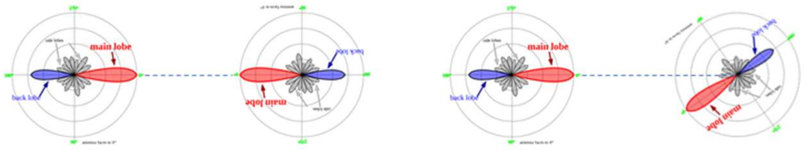
The actual side lobe level of an antenna usually is not specified, although (typical) antenna diagrams might be provided. Specified are maximum levels (side lobes are below a given level). Averages are (much) lower than the specified maximum. Side lobe levels are specified with respect to the maximum gain of the antenna. The absolute value of a side lobe gain is calculated by

$$G_{sla} = G_A - A_{sl}$$

where:
G_{sla} is absolute side lobe gain
G_A is antenna gain (main lobe gain)
A_{sl} is side lobe attenuation (the amount the side lobe is lower than the main lobe).

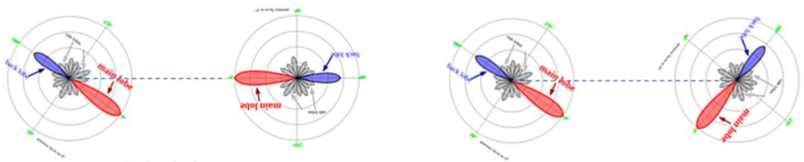
Radar antennas usually rotate or perform a scan, either by mechanical or electronic means. Due to this rotation, the antennas of the source radar and the victim radar will have changing angles towards each other. The following can occur, see also Figure 3-2:

- Main lobe on main lobe
  The two main lobes are directed towards each other.
  The specified antenna gain is used for G_T and G_R.
- Main lobe on side lobe
  The main lobe of the source radar points at the victim radar, the victim radar is receiving the signal via its side lobe.
  For G_T the specified antenna gain is used. For G_R the specified antenna gain minus the side lobe attenuation is used.
- Side lobe on main lobe
  A side lobe of the source radar points at the victim radar, the main lobe of the victim radar points towards the source radar and receives the interfering signal via its main lobe.
  For G_R the specified antenna gain is used. For G_T the specified antenna gain minus the side lobe attenuation is used.
- Side lobe on side lobe
  A side lobe of the source radar points at the victim radar, and a side lobe of the victim radar points towards the source radar and receives the interfering signal via that side lobe.
  For G_T the specified antenna gain minus the side lobe attenuation is used. For G_R the specified antenna gain minus the side lobe attenuation is used.



Main beam on main beam

Main beam on side lobe



Side lobe on main beam

Side lobe on side lobe

Figure 3-2 Antenna to antenna positions.

The side lobe on side lobe situation is a specific case:

- This will be the most common case.
- The two radars have an additional coupling mechanism, the radar signals are reflected by objects in the environment (e.g. a ship or large building) and create additional pathways for the signals to travel from one antenna to the other, see also Figure 3-3.
  This effect occurs also for the other cases, but are far less significant.

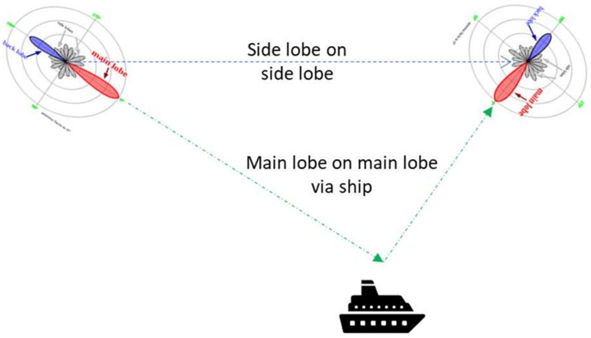


Figure 3-3 Side lobe on side lobe and main lobe main lobe reflection via ship.

This reflection on a target adheres to the bistatic radar equation (bistatic radar = transmit and receive antenna not on the same location):

$$P_r = \frac{P_t G_t G_r \lambda^2 \sigma}{(4\pi)^3 R_t^2 R_r^2}$$

where:
P_r is received power [W]
P_t is transmitted power [W]
G_t is transmitter antenna gain
G_r is receiver antenna gain
λ is wavelength of the radar signal [m]
σ is bistatic radar cross section (RCS) [m^2]
R_t is range (or distance) from transmitter to target [m]
R_r is range (or distance) from receiver to target [m].

Note that this equation transforms to the normal radar equation if transmitter and receiver are on the same spot (R_r=R_t and G_t = G_r).

3.3 Radar to radar interference mechanisms

Radars can cause interference to each other, assuming the mutual coupling is strong enough to cause interference. As can be seen in Table 3.2, we have nine possible interference mechanisms, that all will be described in more detail.

Table 3.2 Interference mechanisms: source victim matrix.

		Source radar type		
	Radar signal	**Short pulse**	**Long pulse**	**CW**
Victim radar type	**Short pulse**	Short - short	Short - long	Short - CW
	Long pulse	Long - short	Long - long	Long - CW
	CW	CW - short	CW - long	CW – CW

3.3.1 *Short pulse to short pulse interference*

If the radars operate at the same frequency (have overlap in their frequency bandwidth) they will receive each other's transmitted radar pulses and display them as (false) target. Given that the systems are not synchronized, the false target appears at varying distances and locations, giving rise to their name: running rabbits, see Figure 3-4.

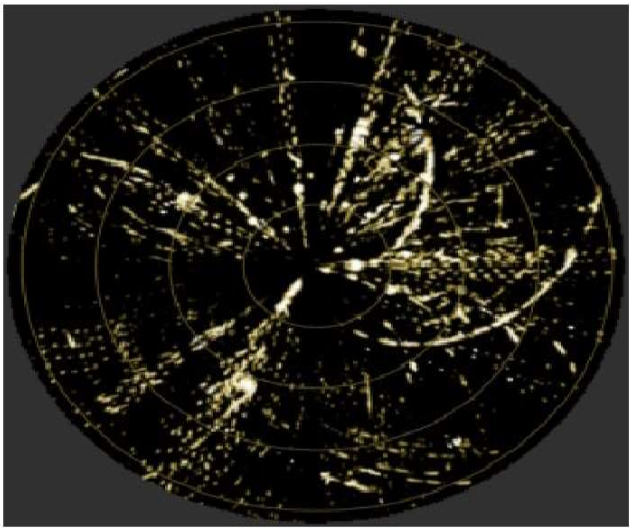


Figure 3-4 Running rabbits appearing as spirals on the radar screen.

This running behaviour make them easy to suppress, as will be discussed in Section 3.5.

The radar is as sensitive to short pulses of other radars, as to its own pulses.

3.3.2 *Short pulse to long pulse interference*

When a short transmit pulse is received by a radar designed to use long pulses, this short pulse will enter the pulse compressor. The pulse compressor shows here a kind of reciprocal behaviour: the short pulse is stretched (to twice the length of the long pulse) and at the same time lowered in amplitude (the energy content remains the same).

Due to the low value and relative long duration (after the pulse compressor), the short pulse manifests itself by an increase of the noise+clutter[3] level. The stretched short pulse can have has a length of tens of microseconds, which equals several kilometres. As a consequence the noise+clutter level is increased in an area of several kilometres.

The radar is less sensitive to short pulses of other radars, as to its own signal. The difference is in the order of the pulse compression ratio.

3.3.3 *Short pulse to CW interference*

What happens when a short radar pulse is received by a FMCW receiver?
From Fourier analysis it is known that this short pulse has a bandwidth of (see also Section 3.1.1):

$$B = {}^{1}/_{\tau}$$

The short pulse with the high bandwidth is fed to the processing, where all frequencies above f_{max} are filtered. As a result, a small amount of the pulse energy is fed to the processing, this energy is in the order of f_{max}/B.

The energy fed to the processing contains all frequencies up to f_{max} equally, it is white noise. A short pulse received by a FMCW radar results in an increase of the noise level.

The radar is less sensitive to short pulses, the sensitivity is in the order of f_{max}/B less than the sensitivity to its own (FM)CW signal.

3.3.4 *Long pulse to short pulse interference*

The transmission and reception are at the same frequency and probably have comparable bandwidth (given that they might also have similar resolution requirements).

The long pulse is fully or partly within the bandwidth of the receiver of the short pulse radar system and is processed as a “normal” radar echo. Due to the long duration of the pulse, the echo will be displayed as an extended target, oriented axially towards the (receiving short pulse) radar. As with the “running rabbits” in Section 3.3.1, these echoes will appear randomly.

The radar is as sensitive to long pulses of other radars, as to its own pulses.

---

[3] Clutter is any unwanted radar signal, for example for a ship radar reflections from the waves or from raindrops are clutter. For a rainfall radar, reflections from raindrops aren’t clutter, however reflections from birds are. The opposite is the case for a bird detection radar.

3.3.5 *Long pulse to long pulse interference*

When a long transmit pulse is received by a radar designed to use long pulses, this long pulse will enter the pulse compressor. The pulse compressor only "compresses" pulses that have the same modulation as 'its own transmitted pulses". We now can discriminate two situations:

- The modulation is the same
  The interference on the receiving radar is as described in Section 3.3.1, we have running rabbits.
- The modulation is not the same
  As for the short pulse, the pulse compressor shows a kind of reciprocal behaviour: the interfering long pulse is stretched and at the same time lowered in amplitude (the energy content remains the same). The amount of stretching and power level depends on the modulation difference.
  Due to the low value and relative long duration (after the pulse compressor), the interfering long pulse manifests itself by an increase of the noise+clutter level. The stretched interfering long pulse can have has a length of tens of microseconds, which equals several kilometres. As a consequence the noise+clutter level is increased in an area of several kilometres.
  The area with the higher level of noise + clutter occurs at changing locations. In the area with increased noise + clutter, the victim radar is desensitized which can be dangerous, especially because there is no indication for this desensitization.

The radar is less sensitive to long pulses of other radars, as to its own signal. The difference is in the order of the pulse compression ratio. An exception is the case where the modulation is the same.

3.3.6 *Long pulse to CW interference*

The interference is similar to that described in Section 3.3.3.

The radar is less sensitive to long pulses, the sensitivity is in the order of f_{max}/B less than the sensitivity to its own (FM)CW signal.

3.3.7 *CW to short pulse interference*

The part of the FMCW modulation that is within the bandwidth of the short pulse radar will be detected and processed. Given the relatively large bandwidth of many short pulse radar systems, either the full or a large part of the FMCW sweep will be within the bandwidth of the short pulse radar.

In case the transmitted FMCW signal is within the bandwidth of the short pulse radar, the following can happen:

- The radar processes the FMCW signal. Radars do have a system for "automatic gain control", usually a CFAR system (CFAR=Constant false Alarm Rate). This system will decrease the gain until the FMCW signal is no longer visible on the radar screen.
  This effectively blinds the radar screen, the remaining radar sensitivity might be such that only large targets, or even no targets at all, are shown. The level of blinding (target sizes that are suppressed) increases with increasing FMCW interference level.
- Most radars have STC, Sensitivity Time Control, this circuit decreases the gain for nearby targets (nearby targets do have high signal strengths). Due to this

mechanism, “blinding” of the radar only occurs above a given distance.
This leads the operator to believe the radar performs normally, he sees nearby targets. However, above a given distance the radar is blinded as explained in the previous bullet.

- As the previous bullet points above, but the radar might recognize the exceptional signal level. The gain will not be reduced fully, so the FMCW signal will become visible on the radar screen “as an abundance of light” (target everywhere) or as “spokes” as the antenna is rotating.
  The advantage: the operator is aware of the interference.

In short:

- Short pulse radars are very sensitive to FMCW interference.
- The radar is as sensitive to CW as to its own pulses.

3.3.8 *CW to long pulse interference*

The CW signal will be processed by the pulse compressor of the long pulse radar system. In a similar way as for the short pulse and the long pulse (see sections 3.3.2 and 3.3.5), the CW signal will be suppressed (it cannot be stretched, being already continuous). Also, the CW signal manifest itself as an increase of the noise level.

The radar is less sensitive to CW as to its own signal. The difference is in the order of the pulse compression ratio.

3.3.9 *CW to CW signal interference*

FMCW radars measure the frequency difference between transmitted and received signal, and only differences smaller than f_{max} are processed (see Section 3.1.3). If radars do have a different sweep rate (sweep rate = B/t_{sweep}, see Section 3.1.3), the situation. is equal to that described in Section 3.3.3. There is an energy reduction in the order of f_{max}/B.

If the radars do have an equal sweep rate and sweep time (so actually the radars are the same), there is a small chance (order $p = f_{max}/B$) that the signal of the source radar differs f_{max} or less with the receiving transmit signal, thereby giving rise to a false target. Given that the radars are not synchronized, this will give rise to a “running rabbit like behaviour” just as described for short pulse radars in Section 3.3.1.

The radar is less sensitive to CW of other radars, the sensitivity is in the order of f_{max}/B less than the sensitivity to its own (FM)CW signal. For equal radars, there is a small chance (order $p = f_{max}/B$) that the sensitivity is equal to that for its own FMCW signal.

3.3.10 *Summary*

The interference described in the previous sections is summarized in Table 3.3. it is assumed that the mutual coupling as described in Section 3.2 is strong enough to cause interference. The relative sensitivity (S_{rel}) is also noted, and defined as the sensitivity to the interfering signal divided by the sensitivity to its own signal. For similar/equal radars, the relative sensitivity is always one and there is a running rabbit behaviour.

Table 3.3 Resulting relative source-victim sensitivity.

		Transmitted signal from source radar		
	Radar signal	**Short pulse**	**Long pulse**	**CW**
Received signal by victim radar	**Short pulse**	Running rabbits S_{rel} = 1	Long target with running rabbit behaviour S_{rel} = 1	Blinding of the radar (above a given range) S_{rel} = 1
	Long pulse	Increase in noise+clutter S_{rel} = PCR	Increase in noise+clutter Running rabbits for equal modulation S_{rel} = PCR	Small noise level increase. S_{rel} = PCR
	CW	Small noise level increase. $S_{rel} = f_{max}/B$	Small noise level increase. $S_{rel} = f_{max}/B$	Small noise level increase. Running rabbits for equal radars $S_{rel} = f_{max}/B$

Note:
The speed of the running rabbit behaviour is depending on the small differences in timing between the two radars (the difference in sweep rate, sweep time, pulse repetition frequency). The smaller the difference, the slower the movement. In the academic case of two synchronized radars, the running rabbits would become stationary false targets.

3.4 Distance

The interference level is determined also by the distance between interfering and interfered radar. The attenuation (free space attenuation) is inverse-quadratic with the distance, as is reflected in the radio equation.

There are numerous conditions whereunder the free space attenuation model is no longer valid:

- Fresnel zone
  If an object is near the radar-radar trajectory, it can cause reflections that affect the signal level in either a positive of negative way. Whether signal level increases or decreases is determined by the rank of the Fresnel zone, see Figure 3-5 obtained from Reference [7].

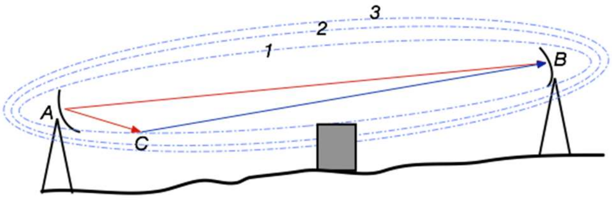


Figure 3-5 Fresnel zones (1, 2, 3 shown). A signal from radar A is reflected by object C and received by radar B, Reference [7].

- Blocking
  Especially on land, the signal also can be blocked by large buildings or by vegetation.

- Radar horizon
  When the distance is too large, the radar antennas go below the horizon, due to the earth's curvature, as is shown in Figure 3-6. the radar horizon is a little "farther away" than the optical horizon, given the tendency of radar and radio waves to follow the earth's curvature (assuming an earth radius of 4/3 the real radius gives the correct distance to the radar horizon). Of course, the radar horizon is also determined by the height of both antennas.
  Typical values for the radar horizon are less than 10 km for low antennas as found on small cargo ships, fisherman boats and yachts. Several tens of km can be reached for antennas on high towers.
  As with the optical horizon, it is possible to see large (high) objects beyond the horizon.

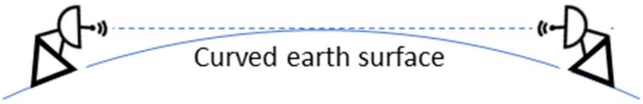


Figure 3-6 Radar horizon.

- Atmospheric conditions
  Rain, water vapor and aerosols will affect the attenuation.

- Anomalous propagation
  This is a specific kind of atmospheric condition. Reflections to layers in the atmosphere allow radar waves to travel much further than the horizon. As such, object beyond the horizon can be visible, and radars can interfere even when they are well beyond the radar horizon.

All the factors discussed in this section are situation specific: atmosphere, antenna height, environment (buildings and vegetation). As a consequence, in this document the free space model is used, while being aware of the limitations. Given that in most cases we are unaware of antenna height, a nearby horizon is assumed, limiting the free space model to about 10 km.

3.5 Mitigation techniques

Radars do apply some techniques that help to mitigate the effect of interfering radar signals. These techniques are described in this section. Some mitigation techniques imply the transmit chain and are hence subject to licensing and frequency management.

3.5.1 Frequency separation

The easiest way to avoid interference is to use frequency separation: radars operate at different frequencies. This of course requires radars to have sufficient suppression of frequencies other than their own transmit frequency. As can be seen in Section 1.3, frequency separation is used to avoid interference between various application domains (air and maritime).

Note that magnetron radars cannot be exactly tuned to a given frequency, as is explained in Section 3.1.1.

This mitigation technique can be enforced by licensing.

3.5.2 Post Detection Binary Integration

When a radar is transmitting pulses towards a target, a number of pulses (usually 5 to 7) is transmitted before the antenna has rotated so much that the target is no longer visible. The Post Detection Binary Integration counts how many times the target is detected from all transmitted pulses and then applies a threshold of N-out-of-M (e.g. 3 out of 5).

This technique is used to increase detection probability while decreasing false alarm rates. As such, running rabbits (false alarms) are also suppressed.

Given the movement of the running rabbit, the received signal does not meet the N-out-of-M criterion. Note that, if the PRF of both radars are the same (and they have a stable frequency reference), the movement might be so slow that the criterion is met and the running rabbit becomes visible.

3.5.3 Dead zone

This method implies an inactive “dead zone” (“transmitter off” period) between the transmission of two “sweeps” for FMCW radars. The dead zone method acts as a mitigation technique for interference from pulse radars and pulse compression radars.

The concept is shown in Figure 3-7. On top the pulse scheme of a pulse radar is shown, including the received pulse, just as shown in Figure 2-2. The bottom part shows the FMCW signal and the dead zone (compare to Section 3.5.4). The FMCW signal might cause interference on a pulse radar and on a pulse compression radar. On one hand, this may result in all kind of fake target signals in the victim radar, on the other hand, it also might desensitize the victim radar so the receive pulses might be ignored.

The fake targets only appear during transmission of the FMCW signal. The fake targets will disappear as soon as the FMCW signal ends, and those targets fail to reach the threshold (see Section 3.5.2) and the fake target is suppressed.

No interference takes place during the dead zone of the FMCW radar. During the dead zone normal operation of the pulse radar and the pulse compression radar is possible. If the dead zone is long enough, so the received signal of the target is acquired a sufficient number of times, then the target signal will meet the threshold of the post detection binary integration and the target will be visible on the radar screen.

In order for this mitigation technique to be effective, FMCW sweep time needs to be short (fake echoes do not meet the threshold) and dead zone needs to be long (so that real targets can meet the threshold). For example the Broadband 3G radar has a sweep time of 1.3 ms and a dead zone of 3.7 ms. If the victim radar has a pulse repetition interval of 1 ms, then only one or two fake target returns can occur in the sweep time, whereas at least 3 and often 4 returns of real targets are received in the dead zone. A 3 out of 5 threshold will reject all fake targets while passing all real targets.

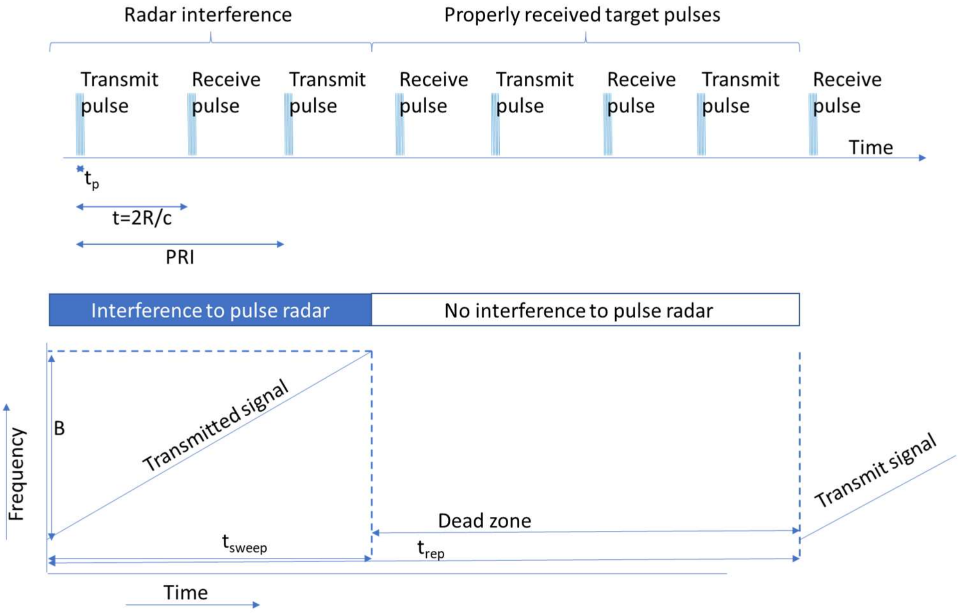


Figure 3-7 Dead zone interference mitigation.

This mitigation technique can be enforced by licensing.

3.5.4 *Varying repetition time*

This method varies the sweep rate and/or the sweep time of FMCW radars. As with the dead zone of Section 3.5.3, it might use an inactive “transmitter off” period between the transmission of two “sweeps”. By varying this transmitter off period randomly, echoes of interfering FMCW have a strong “running rabbit” behaviour (move fast) and are hence easily suppressed by post detection binary integration as described in Section 3.5.2.

The upper part of Figure 3-8 shows the “normal” operation of FMCW, where sweeps are equal and immediately repeated. As a consequence, the repetition time $t_{rep} = t_{sweep}$. The lower part shows the mitigation technique, the repetition time is larger than the sweep time. The repetition time is varied randomly.

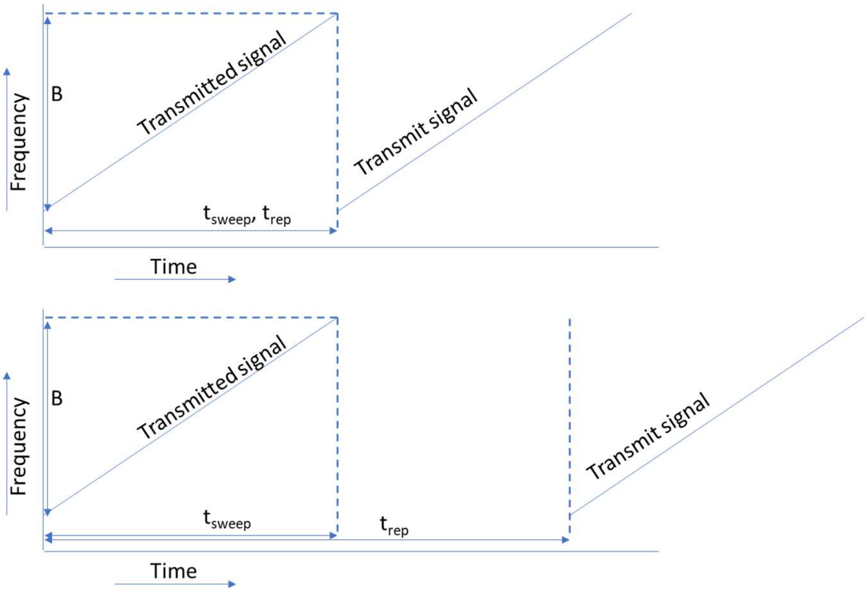


Figure 3-8 Varying repetition time for FMCW operation.

This mitigation technique can be enforced by licensing.

3.5.5 *Varying sweep time*

By varying the sweep time while keeping the repetition time constant, the mitigation becomes even more effective, as is explained in Figure 3-9. The frequency difference of interfering sweeps (even of a similar radar) with the transmitted signal will vary within the sweep time, so it does not give rise to a target signal. The received energy exhibits itself as noise, the most of this energy is beyond f_{max} and will be suppressed. So the method suppresses interference at the expense of a small increase of noise level.

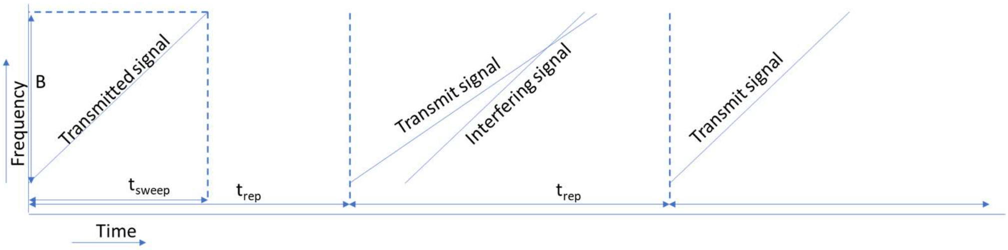


Figure 3-9 Mitigation by varying sweep time.

The Broadband 3G radar uses the concept of variable sweep time. The repetition frequency is fixed at 200 Hz, so $t_{rep} = 1/f_{rep} = 1/200 = 5$ ms. The sweep time varies randomly, $t_{sweep} = 1.3$ ms ± 10%.

This mitigation technique can be enforced by licensing.

3.5.6 *Sector blanking*

Sector blanking is used to avoid the radar transmitting and receiving in given directions, for example a coastal surveillance radar transmits towards the sea, but transmission and reception is interrupted when the antenna is facing landwards.

Sector blanking can also be used to avoid interference between radars on fixed locations.
Transmissions in the direction of the victim radar is interrupted and interference is avoided. The width of the sector that has to be blanked is in the order of the antenna beam width, implying the source radar is blind in this sector. Given the blanked sector is only in the order of the antenna beam width (in the order of a degree), this is often acceptable from an operational point of view.
Also, reception in the direction of a source radar can be interrupted, thereby mitigating interference from this source radar. Again, the necessary width of the blanked sector is in the order of the antenna beam width.

3.5.7 Constant false Alarm Rate

With Constant False Alarm Rate (CFAR) the average noise + clutter level of the radar receiver is calculated. Upon this calculated level a threshold is applied. If the received radar signal is above this threshold, then a valid target is received. The CFAR filter thereby effectively suppresses noise and clutter. Targets of sufficient strength are displayed on the radar screen.

Interfering signals that increase the noise+clutter level, also increase the threshold and cause the interfering signal not to be visible. The drawback of this filter is the reduced sensitivity to received radar signals (of its own transmitter), thereby also suppressing valid small targets. The radar is desensitized.

3.5.8 Polarization

Radars generally receive signals with the same polarization than they transmit. If the transmitting antenna of the interfering radar has a different polarization than the receiving antenna of the victim radar, the interfering signal is suppressed. The amount of suppression is given in Table 3.4. Note that the table is symmetrical relative to the diagonal.

Table 3.4 Suppression for different polarisations.

Transmit polarisation Receive polarisation	Horizontal	Vertical	Left hand circular	Right hand circular
Horizontal	0 dB	10 - 20 dB	3 dB	3 dB
Vertical	10 - 20 dB	0 dB	3 dB	3 dB
Left hand circular	3 dB	3 dB	0 dB	10 - 20 dB
Right hand circular	3 dB	3 dB	10 - 20 dB	0 dB

This is only valid for line of sight “coupling” between the antennas. In case of “main lobe on main lobe via target”, polarization is changed and the suppression gets in the order of 3 dB. Also the motion of the ship will affect the polarization of the ship borne radar.

This mitigation technique can be enforced by licensing.

4 Interference

To evaluate the interference mechanisms given in the previous chapter, we will start with the selection of a set of “typical radars” that we will use in our evaluation.

4.1 Typical radars

The designation given in Section 1.3 limits the application of the radars to 2700 - 3300 MHz (S-band) and 8750 - 10400 MHz (X- band). Nevertheless, the list of existing different radar types is virtually endless. Fortunately, radars for a given application usually have similar specifications, so we will take a typical radar for each application, and will discuss what deviations we can expect.

The application areas given in Section 1.3 are based on the classical use of radar: air traffic control and maritime use. Contemporary applications as drone detection and bird migration are not mentioned. Weather radar is recognized and the band 9500 - 9800 MHz is allocated for this application. This part of the band is dedicated to atmospheric research, not limited to radar. Only

Maritime radar can be divided in land based and ship-borne radar.

The land based radars are either for VTS (Vessel Traffic Services) or for Coastal Surveillance, where the same radars are used for both applications. These radars operate almost exclusively in the band around 9 GHz (X-band), due to the (three times) higher azimuth resolution (for the same antenna dimensions). This advantage mostly exceeds the improved all weather capability of S-band radar operating around 3 GHz.

The shipborne radars are also to a large extent X-band radars. However, IMO (international Maritime Organization) requires all sea going vessels above 300 ton to have two radars, one of which shall be S-band[4].

Air traffic control radars are used for ‘en route” monitoring (long range, usually L-band), Air Surveillance (medium range, up to about 100 km, S- band), Precision (Runway) Approach and Surface Movement (both X-band). Precision Approach radars, however, are not used in the civil domain, instead ILS (instrument Landing System) is used. Nowadays also GPS based systems are used (RNAV, Area Navigation and RNP, Required Navigation Performance).

The new applications such as bird and drone detection use both X- and S-band radar. New rainfall rate radars are also used in X-band[5].

For each application, band and radar type we have selected a “typical radar”, following the analysis given above.

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[4] Up to 500 ton, there can be a caveat to use two X-band radars.

[5] Most conventional weather radars operate in C-band.

The S-band radars:

- Shipborne maritime radar,
  Furuno pulse radar,
  A similar radar is used as bird detection radar, the horizontal component of the ROBIN Flex 3D system.
- Air traffic control radar for Air Surveillance,
  STAR2000 pulse compression radar used at Schiphol Airport.

The X-band radars:

- Shipborne maritime radar,
  Furuno FAR 2127 pulse compression radar.
- Shipborne maritime radar,
  Broadband 3G FMCW radar.
- Maritime VTS radar,
  Terma SCANTER 5202 pulse compression radar.
- Air traffic control radar for Surface Movement,
  Terma 5602 pulse compression radar.
- Bird detection radar, FMCW radar vertical component of the ROBIN FLEX-3D system.
- Drone detection radar,
  ROBIN ELVIRA FMCW radar.
- Weather/rainfall radar,
  FMCW radar by Technical University Delft.

More specifics of these “typical radars” are given in Table 4.1 on the next page. A larger version is available in the Appendix A. Note that:

- These specifications are taken from open literature and websites and might be inaccurate.
- For missing specifications, expert judgements are taken, often based on CARPET [4] calculations.
- To keep the table easy to understand, not all setting values are given.

Table 4.1 Typical radar systems used in the study.

Brand/ type	Description	Waveform	Frequency (MHz)	Receiver bandwidth (MHz)	Sweep bandwidth (MHz)	Transmit power (dBW)	Antenna gain (dBi)	EIRP (dBW)	Beamwidth	Pulse width	Pulse repetion frequency
THALES Star2000	Air surveillance radar	puls compr	2895	2	2	44,8	34,3	79,1	2,4°	98 µs	1,1 kHz
Furuno FAR-6167DS	Shipborne maritime	puls	3050	30		47,8	26,8	74,6	1,8°*25°	80 ns	1,9 kHz
Furuno FAR 2127	Shipborne maritime	puls	9410	3-20-40		44	33,2	77,2	0,95°*20°	0,07-1,2 µs	600-3000 Hz
Lowrance Broadband 3G	Shipborne maritime	FMCW	9300-9400	75	75	-10	24	14	5,2°*25°	1,3 ms	200 Hz
Terma Scanter 5200	Land based maritime VTS	puls compr	9000-9200 or 9225-9500	40	40	23	38	61	0,36°*13°	100 µs	1 kHz
Terma Scanter 5602	Airport Surface movement	puls comp	9410	40	40	23	35	58	0,7°*13°	100 µs	1 kHz
Robin Flex-3D	Bird detection	FMCW	9650	100	100	-4	33,7	29,7	0,8°*20°	Unknown	Unknown
Robin Elvira	Drone detection	FMCW	9250	50	50	6	39	45	2,1*2,1	Unknown	Unknown
TUD	Rainfall radar	FMCW	9200-9500	7,5-50	7,5-50	7,4	39,3	46,7	2,1 * 2,1	Unknown	Unknown

4.2 Interference calculation

This section describes how the interference level from one radar to another is calculated.

Starting point are the relevant factors that determine the interference, as described in Chapter 3. These factors determine the level of perceived interference, this level actually present at the output of the radar (and entering either the radar post processor or the display processor).

This perceived interference level is calculated in three steps:

- Calculation of the level of interfering energy at the input of the victim radar. The radio equation in Section 3.2 is used.
- Calculation of the signal level in overlapping bandwidth. The part of the instantaneous band used by the source radar that is within the bandwidth of the victim radar will cause more interference than the part that is outside this band.
- Calculation of the relative sensitivity. Here the values according to the formulae in Table 3.3 are used.

The interference level is compared to the noise level of the victim radar.

For the calculation of the interference level, a calculation tool has been developed and used, the output of which is shown in Table 4.2. This sheet is used for the analysis in Section 4.3 and is explained in detail. The first analysis of Section 4.3, the interference of an S-band pulse compression radar to a similar radar, is used as an example.

As is described in Section 3.2, the antenna positions play an important role. The top of the sheet notes the used antenna position, in this case a side lobe on side lobe position.

The second section “Interfering radar pulse compression” of the sheet provides the data of the interfering radar. The top line mentions the fact that we have a pulse compression radar. Relevant parameters are the transmit frequency, the bandwidth, the transmit power and antenna gain. The EIRP (Effective Isotropic Radiated Power) is expressed as spectral density, to accommodate bandwidth differences between interfering and interfered radar. For side-lobe analysis, also the antenna side lobe level is needed.

Note that the antenna side lobe level is often specified by antenna manufacturers as a “lower than” value, rather than an average. As a result, actual interference levels might be lower by 10 dB or more. If needed and appropriate, a best estimate for the average side lobe level will be used.

The third section “Radio propagation” provides the FSA (Free Space Attenuation) for the specified distance between interfering and interfered radar. Many calculations are made for a distance of 1 km. Then results can be compared. Reflections on objects near to the propagation path (see also Section 3.4 on Fresnel zone) are not taken into account. These reflections can cause differences in the order of 6 dB.

The fourth section “Interfered radar pulse compression” provides the data of the radar to be interfered. Also here an antenna side lobe level is included. The noise figure is provided to compare the interference with the radars noise level, the out-of-band rejection is provided to analyse interference in case the source radar transmits outside the band of the victim radar.

The fifth section “Interference level” contains the analysis. The first step is the calculation of the power received by the victim radar and is determined by the sum of:

- The EIRP of the source radar. In case of side lobe analysis (which is the case in the example), this value is lowered with the side lobe level of the antenna of the source radar. The fact side lobe level is used is mentioned, including the value.
- The FSA.
- The antenna gain of the victim radar. Also this gain is lowered by the side lobe level in case side lobe analysis is performed.
- In receivers, powers are usually expressed in dBm rather than in dBW (the difference between the two is 30 dB). The conversion is made to facilitate easy understanding.

Table 4.2 Interference analysis sheet.

Interference scenario		**Side lobe on side lobe**		
Interfering radar pulse compression				
		Transmit frequency	[MHz]	2895
THALES	Air surveillance radar	Signal bandwidth	[MHz]	2
Star2000		Transmit power	[dBW]	44,8
		Antenna gain	[dBi]	34,3
		Side lobe level	[dB]	-25
		EIRP	[dBW/MHz]	76,1
radiopropagation		distance	[km]	1
		FSA	[dB]	-101,7
Interfered radar pulse compression				
		Receive frequency	[MHz]	2895
THALES	Air surveillance radar	Receiver bandwidth	[MHz]	2
Star2000		Antenna gain	[dBi]	34,3
		Side lobe level	[dB]	-25
		Noise figure	[dB]	6
		Out of band suppression	[dB]	80
Interference level				
	EIRP interfering radar		[dBW/MHz]	76,1
	EIRP to interfered radar		[dBW/MHz]	51,1
	Side lobe -25 dB			
	Propagation loss		[dB]	-101,7
	Antenna gain interfered radar		[dBi]	9,3
	Side lobe -25 dB			
	Received power by interfered radar		[dBW/MHz]	-41,3
			[dBm/MHz]	-11,3
	Received signal bandwidth		[MHz]	2
	Received power in signal bandwidth		[dBm]	-8,3
	Relative sensitivity		[dB]	0,0
	Perceived signal level		[dBm]	-8,3
	receiver noise level		[dBm]	-105,0
	I/N		[dB]	96,7
Reflection in the environment				
	Radar Cross section		[m^2]	100
	Distance to "target"		[km]	1
	Both for interferer and interfered radar			
	Reveived power		[dBm]	-9,2668
	I/N		[dB]	95,7

The second step is the calculation of the influence of the interfering signal on the victim radar. The following aspects are taken into account:

- Received signal bandwidth & received power in signal bandwidth.
  Bandwidths of the interfering and interfered radars may differ, as may their transmit frequencies. Only the part of the transmitted/interfering energy that is within the bandwidth of the receiving/victim radar is taken into account. In case there is no overlap in bandwidth, the out-of-band suppression is applied (Received signal bandwidth is zero in that case).

Note: FMCW frequency sweep is long in comparison to the pulse length of pulse and pulse compressor radars. Depending on the frequency of the FMCW radar on a specific moment, it will cause interference or not. The sheet takes into account interference takes place (and hence all transmitted power is received).

- Relative sensitivity
  Radar systems do have a specific sensitivity to signals “other than their own transmitted signal”, as is explained in Section 3.3. This factor is taken into account.
  Note: the relative signal sensitivity of the pulse compressor radar is equal to the pulse compression ratio. However, in the sheet it is compared to noise to calculate the interference to noise ratio. As both noise and the interfering radar signal do not compress (correlate) in the pulse compressor, the relative sensitivity used is 1. In the pulse compressor the radar pulses increase with a factor of PCR, whereas noise and the interfering signal do not.

The perceived interfering signal is compared to the noise level, yielding the Interference to Noise level (I/N). Large interference levels can cause saturation effects (here the IP3 level of the input stage is important). However interference is eminent long before saturation is reached, hence it is not taken into account.

The sixth section “Reflection in the environment” takes reflection in the environment into account. The reflection is evaluated for the (arbitrary chosen) geometry as shown in Figure 4-1. Also the radar cross section of the target is arbitrary chosen at 100 m^2. Also here the comparison to the noise level is made.

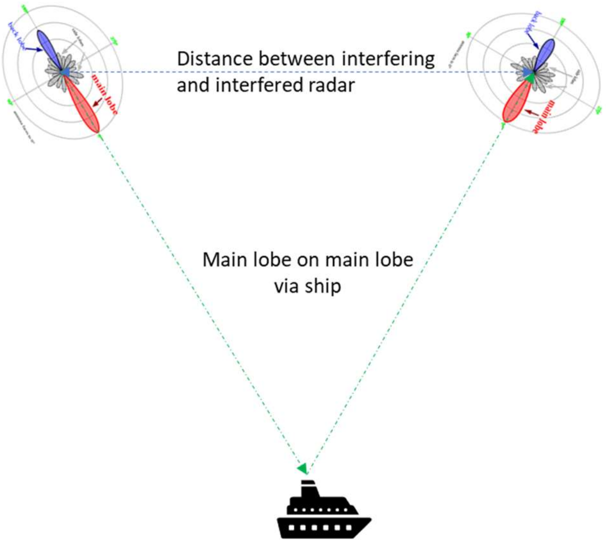

Figure 4-1 Geometry of reflection in the environment. The distance to the target (a ship is just used as example) is equal to the distance between the radars.

It should be underlined that the sheet provides an order of magnitude, especially for side lobe on side lobe that heavily depends on exact side lobe levels and antenna positions. Also, the reflection in the environment is just a specific case. Moreover, a simple free space attenuation model is used, which is adequate for line of sight conditions (radars can “see” each other, free Fresnel zone).

However, this is exactly what is needed, given that we are working on guidelines that can be used for a variety of radar systems, each with their variety in parameters.

As such, the exact specifications of the used “typical radars” are not that relevant and the use of expert judgement for omitting specification is fully justifiable. As an example, for all radars a noise figure of 6 dB is assumed, although in most cases it will be better.

Organizations like ITU (International Telecommunication Union) use a maximum allowable I/N (Interference to noise) level of -6 dB. Although less relevant (our calculations are only a rough order of magnitude) we will use this limit also.

Should a thorough analysis be needed for a specific situation, then more accurate models need to be used taking into account propagation and terrain (e.g. CARPET [4] and TERPEM).

4.3 Interference analysis

In this section the mutual interference is analysed for the “typical radar systems”. A distinction is made between S-band and X-band, given that these radars virtually do not interfere one another.

Both in S-band and in X-band there is a clear separation between frequency bands for air traffic control and for maritime use. Also, X-band has a separate frequency band for meteorological research.

The use of frequency separation is a very effective means to avoid interference.

4.3.1 S-band radar pulse & pulse compression

As ship and ATC radars are already separated in frequency, interference in S-band is merely ship-to-ship radar, or ATC to ATC radar.

ATC-to-ATC radar interference can be mitigated by frequency separation. The available band is 200 MHz wide so the available frequency band provides ample possibilities for frequency management.

The evaluation for ATC to ATC radar interference for radars operating at the same frequency has already been given in Table 4.2 that is used for explanation in Section 4.2.

The evaluation has been performed for a low 1 km distance and of course the radars are interfering at this distance. Note however that the I/N levels are below 100 dB, notwithstanding the side lobe levels are exceptionally high at -25 dB. These radars usually have a dynamic range of 100 dB or more, so the post detection binary integration will perfectly cancel out the “running rabbits”.

The case of frequency separation is shown in Table 4.3. The interference distance is 10 km. Note that the I/N levels are below 0 dB, even with high side lobe levels.

Table 4.3 Evaluation ATC radars with frequency separation.

Interference scenario		**Side lobe on side lobe**		
Interfering radar pulse compression				
		Transmit frequency	[MHz]	2895
THALES	Air surveillance radar	Signal bandwidth	[MHz]	2
Star2000		Transmit power	[dBW]	44,8
		Antenna gain	[dBi]	34,3
		Side lobe level	[dB]	-25
		EIRP	[dBW/MHz]	76,1
radiopropagation		distance	[km]	10
		FSA	[dB]	-121,7
Interfered radar pulse compression				
		Receive frequency	[MHz]	2890
THALES	Air surveillance radar	Receiver bandwidth	[MHz]	2
Star2000		Antenna gain	[dBi]	34,3
		Side lobe level	[dB]	-25
		Noise figure	[dB]	6
		Out of band suppression	[dB]	80
Interference level				
	EIRP interfering radar		[dBW/MHz]	76,1
	EIRP to interfered radar		[dBW/MHz]	51,1
	Side lobe -25 dB			
	Propagation loss		[dB]	-121,7
	Antenna gain interfered radar		[dBi]	9,3
	Side lobe -25 dB			
	Received power by interfered radar		[dBW/MHz]	-61,3
			[dBm/MHz]	-31,3
	Received signal bandwidth		[MHz]	0
	Received power with out of band suppression		[dBm]	-108,3
	Relative sensitivity		[dB]	0,0
	Perceived signal level		[dBm]	-108,3
	receiver noise level		[dBm]	-105,0
	I/N		[dB]	-3,3
Reflection in the environment				
	Radar Cross section		[m^2]	100
	Distance to "target"		[km]	10
	Both for interferer and interfered radar			
	Reveived power		[dBm]	-129,27
	I/N		[dB]	-24,3

Ship-to-ship radar interference is mostly mitigated by post detection binary integration. Any way of frequency management is hardly impossible, ships from all over the world are passing Dutch waterways.

A second mitigation mechanism in use is the modulation of the pulse compression.

Ship-to-ship radar interference is comparable to ATC-to-ATC radar interference, as can be seen from Table 4.4. Also here, I/N levels are well below 100 dB, running rabbits will be effectively suppressed by post detection binary integration.

Table 4.4 Ship-to-ship radar interference.

Interference scenario		**Side lobe on side lobe**		
Interfering radar pulse				
		Transmit frequency	[MHz]	3050
Furuno	Shipborne maritime	Signal bandwidth	[MHz]	30
FAR-6167DS		Transmit power	[dBW]	47,8
		Antenna gain	[dBi]	26,8
		Side lobe level	[dB]	-25
		EIRP	[dBW/MHz]	59,8
radiopropagation		distance	[km]	1
		FSA	[dB]	-102,1
Interfered radar pulse				
		Receive frequency	[MHz]	3050
Furuno	Shipborne maritime	Receiver bandwidth	[MHz]	30
FAR-6167DS		Antenna gain	[dBi]	26,8
		Side lobe level	[dB]	-25
		Noise figure	[dB]	6
		Out of band suppression	[dB]	60
Interference level				
	EIRP interfering radar		[dBW/MHz]	59,8
	EIRP to interfered radar		[dBW/MHz]	34,8
	Side lobe -25 dB			
	Propagation loss		[dB]	-102,1
	Antenna gain interfered radar		[dBi]	1,8
	Side lobe -25 dB			
	Received power by interfered radar		[dBW/MHz]	-65,5
			[dBm/MHz]	-35,5
	Received signal bandwidth		[MHz]	30
	Received power in signal bandwidth		[dBm]	-20,7
	Relative sensitivity		[dB]	0,0
	Perceived signal level		[dBm]	-20,7
	receiver noise level		[dBm]	-93,2
	I/N		[dB]	72,5
Reflection in the environment				
	Radar Cross section		[m^2]	100
	Distance to "target"		[km]	1
	Both for interferer and interfered radar			
	Reveived power		[dBm]	-21,72
	I/N		[dB]	71,5

As an illustration, also the main beam on main beam interference is analysed, as is shown in Table 4.5. Already at 40 km distance (about the distance where line of sight occurs for large vessels) the interference to noise ratio is close to 100 dB. At shorter distances, they will be even higher. Radars can handle these levels however they will temporarily “blind” the radar. One should note however that the radar beam is 1.8° wide, the chance of “seeing” the main beam of a rotating radar antenna is hence 1.8/360 = 0.005. For main beam on main beam, both antennas have to face each other, the chance of this happening is $0.005^2 = 2.5 \times 10^{-5}$.

Table 4.5 Main beam on main beam interference.

Interference scenario		**Main beam on main beam**		
Interfering radar pulse				
		Transmit frequency	[MHz]	3050
Furuno	Shipborne maritime	Signal bandwidth	[MHz]	30
FAR-6167DS		Transmit power	[dBW]	47,8
		Antenna gain	[dBi]	26,8
		Side lobe level	[dB]	-25
		EIRP	[dBW/MHz]	59,8
radiopropagation		distance	[km]	40
		FSA	[dB]	-134,2
Interfered radar pulse				
		Receive frequency	[MHz]	3050
Furuno	Shipborne maritime	Receiver bandwidth	[MHz]	30
FAR-6167DS		Antenna gain	[dBi]	26,8
	Main beam	Side lobe level	[dB]	-25
		Noise figure	[dB]	6
		Out of band suppression	[dB]	60
Interference level				
	EIRP interfering radar		[dBW/MHz]	59,8
	EIRP to interfered radar		[dBW/MHz]	59,8
	Main beam			
	Propagation loss		[dB]	-134,2
	Antenna gain interfered radar		[dBi]	26,8
	Main beam			
	Received power by interfered radar		[dBW/MHz]	-47,5
			[dBm/MHz]	-17,5
	Received signal bandwidth		[MHz]	30
	Received power in signal bandwidth		[dBm]	-2,8
	Relative sensitivity		[dB]	0,0
	Perceived signal level		[dBm]	-2,8
	receiver noise level		[dBm]	-93,2
	I/N		[dB]	90,5
Reflection in the environment				
	Radar Cross section		[m^2]	100
	Distance to "target"		[km]	40
	Both for interferer and interfered radar			
	Reveived power		[dBm]	-85,802
	I/N		[dB]	7,4

The probability of main beam on side lobe or side lobe on main beam is both 0.005. The antenna is rotating 360° in two to three seconds, so this happens every 2 to 3 seconds for a very short moment. The signal levels are shown in Table 4.6 for a distance of 1 km, as expected the I/N levels are 25 dB higher (the side lobe level) as in Table 4.4, however they are still less than 100 dB. Mitigation techniques hence are indispensable for proper radar operation.

Also note that in harbour or on water ways, ships can easily approach each other for a distance less than 1 km and momentary blinding of the radar can occur. In most cases, the ship carrying the source radar will remain visible, notwithstanding the blinding (that will suppress many details around and behind the ship).

Table 4.6 Main beam on side lobe interference.

Interference scenario		**Main beam on side lobe**		
Interfering radar pulse				
		Transmit frequency	[MHz]	3050
Furuno	Shipborne maritime	Signal bandwidth	[MHz]	30
FAR-6167DS		Transmit power	[dBW]	47,8
		Antenna gain	[dBi]	26,8
		Side lobe level	[dB]	-25
		EIRP	[dBW/MHz]	59,8
radiopropagation		distance	[km]	1
		FSA	[dB]	-102,1
Interfered radar pulse				
		Receive frequency	[MHz]	3050
Furuno	Shipborne maritime	Receiver bandwidth	[MHz]	30
FAR-6167DS		Antenna gain	[dBi]	26,8
		Side lobe level	[dB]	-25
		Noise figure	[dB]	6
		Out of band suppression	[dB]	60
Interference level				
	EIRP interfering radar		[dBW/MHz]	59,8
	EIRP to interfered radar		[dBW/MHz]	59,8
	Main beam			
	Propagation loss		[dB]	-102,1
	Antenna gain interfered radar		[dBi]	1,8
	Side lobe -25 dB			
	Received power by interfered radar		[dBW/MHz]	-40,5
			[dBm/MHz]	-10,5
	Received signal bandwidth		[MHz]	30
	Received power in signal bandwidth		[dBm]	4,3
	Relative sensitivity		[dB]	0,0
	Perceived signal level		[dBm]	4,3
	receiver noise level		[dBm]	-93,2
	I/N		[dB]	97,5
Reflection in the environment				
	Radar Cross section		[m^2]	100
	Distance to "target"		[km]	1
	Both for interferer and interfered radar			
	Reveived power		[dBm]	-21,72
	I/N		[dB]	71,5

Main conclusion of this section; nearby radars will interfere each other when they operate at the same frequency and interference mitigation techniques are indispensable. This is true also for X-band radars.

4.3.2 *X-band radars, pulse and pulse compression*

In X-band there is a separation of frequency bands for maritime operation and ATC. Interference between radars in these categories can be avoided by frequency separation. Analysis shows I/N values of less than -6 dB for all cases with frequency separation. As an example the out-of-band interference between a maritime Scanter 5202 and a 5602 Surface Movement Radar is given in Table 4.7. I/N interference values are very low, even for the extremely short distance of 1 km. Note that we have “tuned” the 5602 to an ATC frequency where the “typical” radar is in the maritime band (see also Section 4.4.4).

Table 4.7 X-band out-of-band interference.

Interference scenario		**Side lobe on side lobe**		
Interfering radar pulse compression				
		Transmit frequency	[MHz]	9410
Terma	Land based maritime VTS	Signal bandwidth	[MHz]	40
Scanter 5200		Transmit power	[dBW]	23
		Antenna gain	[dBi]	38
		Side lobe level	[dB]	-25
		EIRP	[dBW/MHz]	45,0
radiopropagation		distance	[km]	1
		FSA	[dB]	-111,9
Interfered radar pulse compression				
		Receive frequency	[MHz]	9100
Terma	Airport Surface movement	Receiver bandwidth	[MHz]	40
Scanter 5602		Antenna gain	[dBi]	35
		Side lobe level	[dB]	-25
		Noise figure	[dB]	6
		Out of band suppression	[dB]	80
Interference level				
	EIRP interfering radar		[dBW/MHz]	45,0
	EIRP to interfered radar		[dBW/MHz]	20,0
	Side lobe -25 dB			
	Propagation loss		[dB]	-111,9
	Antenna gain interfered radar		[dBi]	10
	Side lobe -25 dB			
	Received power by interfered radar		[dBW/MHz]	-81,9
			[dBm/MHz]	-51,9
	Received signal bandwidth		[MHz]	0
	Received power with out of band suppression		[dBm]	-115,9
	Relative sensitivity		[dB]	0,0
	Perceived signal level		[dBm]	-115,9
	receiver noise level		[dBm]	-92,0
	I/N		[dB]	-23,9
Reflection in the environment				
	Radar Cross section		[m^2]	100
	Distance to "target"		[km]	1
	Both for interferer and interfered radar			
	Reveived power		[dBm]	-116,91
	I/N		[dB]	-24,9

Interference between pulse radars of the same type show similar results as for S-band, see Table 4.8. I/N values are high but well below 100 dB, allowing for efficient suppression of running rabbits by post detection binary integration.

Table 4.8 Interference between two maritime pulse radars.

Interference scenario		**Side lobe on side lobe**		
Interfering radar pulse				
		Transmit frequency	[MHz]	9410
Furuno	Shipborne maritime	Signal bandwidth	[MHz]	20
FAR 2127		Transmit power	[dBW]	44
		Antenna gain	[dBi]	33,2
		Side lobe level	[dB]	-25
		EIRP	[dBW/MHz]	64,2
radiopropagation		distance	[km]	1
		FSA	[dB]	-111,9
Interfered radar pulse				
		Receive frequency	[MHz]	9410
Furuno	Shipborne maritime	Receiver bandwidth	[MHz]	20
FAR 2127		Antenna gain	[dBi]	33,2
		Side lobe level	[dB]	-25
		Noise figure	[dB]	6
		Out of band suppression	[dB]	60
Interference level				
	EIRP interfering radar		[dBW/MHz]	64,2
	EIRP to interfered radar		[dBW/MHz]	39,2
	Side lobe -25 dB			
	Propagation loss		[dB]	-111,9
	Antenna gain interfered radar		[dBi]	8,2
	Side lobe -25 dB			
	Received power by interfered radar		[dBW/MHz]	-64,5
			[dBm/MHz]	-34,5
	Received signal bandwidth		[MHz]	20
	Received power in signal bandwidth		[dBm]	-21,5
	Relative sensitivity		[dB]	0,0
	Perceived signal level		[dBm]	-21,5
	receiver noise level		[dBm]	-95,0
	I/N		[dB]	73,5
Reflection in the environment				
	Radar Cross section		[m^2]	100
	Distance to "target"		[km]	1
	Both for interferer and interfered radar			
	Reveived power		[dBm]	-22,506
	I/N		[dB]	72,5

In Table 4.9 the interference of a pulse radar to a pulse compression radar is given whereas the opposite is shown in Table 4.10. Also, the I/N values are well above 0 dB but also well below 100 dB. Post detection binary integration is necessary as mitigation technique.

Table 4.9 Pulse radar to pulse compression radar interference.

Interference scenario		**Side lobe on side lobe**		
Interfering radar pulse compression				
		Transmit frequency	[MHz]	9410
Terma	Land based maritime VTS	Signal bandwidth	[MHz]	40
Scanter 5200		Transmit power	[dBW]	23
		Antenna gain	[dBi]	38
		Side lobe level	[dB]	-25
		EIRP	[dBW/MHz]	45,0
radiopropagation		distance	[km]	1
		FSA	[dB]	-111,9
Interfered radar pulse				
		Receive frequency	[MHz]	9410
Furuno	Shipborne maritime	Receiver bandwidth	[MHz]	20
FAR 2127		Antenna gain	[dBi]	33,2
		Side lobe level	[dB]	-25
		Noise figure	[dB]	6
		Out of band suppression	[dB]	60
Interference level				
	EIRP interfering radar		[dBW/MHz]	45,0
	EIRP to interfered radar		[dBW/MHz]	20,0
	Side lobe -25 dB			
	Propagation loss		[dB]	-111,9
	Antenna gain interfered radar		[dBi]	8,2
	Side lobe -25 dB			
	Received power by interfered radar		[dBW/MHz]	-83,7
			[dBm/MHz]	-53,7
	Received signal bandwidth		[MHz]	20
	Received power in signal bandwidth		[dBm]	-40,7
	Relative sensitivity		[dB]	0,0
	Perceived signal level		[dBm]	-40,7
	receiver noise level		[dBm]	-95,0
	I/N		[dB]	54,3
Reflection in the environment				
	Radar Cross section		[m^2]	100
	Distance to "target"		[km]	1
	Both for interferer and interfered radar			
	Reveived power		[dBm]	-41,716
	I/N		[dB]	53,3

Table 4.10 Pulse compression radar to pulse radar interference.

Interference scenario		**Side lobe on side lobe**		
Interfering radar pulse				
		Transmit frequency	[MHz]	9410
Furuno	Shipborne maritime	Signal bandwidth	[MHz]	20
FAR 2127		Transmit power	[dBW]	44
		Antenna gain	[dBi]	33,2
		Side lobe level	[dB]	-25
		EIRP	[dBW/MHz]	64,2
radiopropagation		distance	[km]	1
		FSA	[dB]	-111,9
Interfered radar pulse compression				
		Receive frequency	[MHz]	9410
Terma	Land based maritime VTS	Receiver bandwidth	[MHz]	40
Scanter 5200		Antenna gain	[dBi]	38
		Side lobe level	[dB]	-25
		Noise figure	[dB]	6
		Out of band suppression	[dB]	80
Interference level				
	EIRP interfering radar		[dBW/MHz]	64,2
	EIRP to interfered radar		[dBW/MHz]	39,2
	Side lobe -25 dB			
	Propagation loss		[dB]	-111,9
	Antenna gain interfered radar		[dBi]	13
	Side lobe -25 dB			
	Received power by interfered radar		[dBW/MHz]	-59,7
			[dBm/MHz]	-29,7
	Received signal bandwidth		[MHz]	20
	Received power in signal bandwidth		[dBm]	-16,7
	Relative sensitivity		[dB]	-49,0
	Perceived signal level		[dBm]	-65,7
	receiver noise level		[dBm]	-92,0
	I/N		[dB]	26,2
Reflection in the environment				
	Radar Cross section		[m^2]	100
	Distance to "target"		[km]	1
	Both for interferer and interfered radar			
	Reveived power		[dBm]	-66,737
	I/N		[dB]	25,2

4.3.3 *X-band interference, FMCW radars*

Interference between maritime FMCW radars is given in Table 4.11. Note that these radars already have very low I/N values, implying their performance is not affected by the interferer. The calculation of relative sensitivity takes into account that the sweep rates are not equal (this is actually a mitigation technique used by the Broadband 3G radar). Also the low power and relatively low antenna gain contribute to the low interference.

Table 4.11 Interference between maritime FMCW radars.

Interference scenario		**Side lobe on side lobe**		
Interfering radar FMCW				
		Transmit frequency	[MHz]	9350
Lowrance	Shipborne maritime	Signal bandwidth	[MHz]	75
Broadband 3G		Transmit power	[dBW]	-10
		Antenna gain	[dBi]	24
		Side lobe level	[dB]	-25
		EIRP	[dBW/MHz]	-4,8
radiopropagation		distance	[km]	1
		FSA	[dB]	-111,9
Interfered radar FMCW				
		Receive frequency	[MHz]	9350
Lowrance	Shipborne maritime	Receiver bandwidth	[MHz]	75
Broadband 3G		Antenna gain	[dBi]	24
		Side lobe level	[dB]	-25
		Noise figure	[dB]	6
		Out of band suppression	[dB]	60
Interference level				
	EIRP interfering radar		[dBW/MHz]	-4,8
	EIRP to interfered radar		[dBW/MHz]	-29,8
	Side lobe -25 dB			
	Propagation loss		[dB]	-111,9
	Antenna gain interfered radar		[dBi]	-1
	Side lobe -25 dB			
	Received power by interfered radar		[dBW/MHz]	-142,6
			[dBm/MHz]	-112,6
	Received signal bandwidth		[MHz]	75
	Received power in signal bandwidth		[dBm]	-93,9
	Relative sensitivity		[dB]	-12,4
	Perceived signal level		[dBm]	-106,2
	receiver noise level		[dBm]	-89,2
	I/N		[dB]	-17,0
Reflection in the environment				
	Radar Cross section		[m^2]	100
	Distance to "target"		[km]	1
	Both for interferer and interfered radar			
	Reveived power		[dBm]	-107,25
	I/N		[dB]	-18,0

The interference from maritime FMCW radar to maritime pulse radar is given in Table 4.12. Again, the interference is absent, this is however due to the frequency separation. Table 4.13 shows the situation for the broadband 3G radar tuned to the same transmit frequency as the Furuno. The interference values for a distance of 1 km are just too high, however note we use high levels for the antenna sidelobes. In reality I/N values might be below -6 dB.

However, the dead zone of the broadband 3G radar will allow the pulse radar post detection binary integration system to be effective, as described in Section 3.5.3.

Table 4.12 Interference from FMCW to pulse radar, different frequencies.

Interference scenario		**Side lobe on side lobe**		
Interfering radar FMCW				
		Transmit frequency	[MHz]	9350
Lowrance	Shipborne maritime	Signal bandwidth	[MHz]	75
Broadband 3G		Transmit power	[dBW]	-10
		Antenna gain	[dBi]	24
		Side lobe level	[dB]	-25
		EIRP	[dBW/MHz]	-4,8
radiopropagation		distance	[km]	1
		FSA	[dB]	-111,9
Interfered radar pulse				
		Receive frequency	[MHz]	9410
Furuno	Shipborne maritime	Receiver bandwidth	[MHz]	20
FAR 2127		Antenna gain	[dBi]	33,2
		Side lobe level	[dB]	-25
		Noise figure	[dB]	6
		Out of band suppression	[dB]	60
Interference level				
	EIRP interfering radar		[dBW/MHz]	-4,8
	EIRP to interfered radar		[dBW/MHz]	-29,8
	Side lobe -25 dB			
	Propagation loss		[dB]	-111,9
	Antenna gain interfered radar		[dBi]	8,2
	Side lobe -25 dB			
	Received power by interfered radar		[dBW/MHz]	-133,4
			[dBm/MHz]	-103,4
	Received signal bandwidth		[MHz]	0
	Received power with out of band suppression		[dBm]	-144,7
	Relative sensitivity		[dB]	0,0
	Perceived signal level		[dBm]	-144,7
	receiver noise level		[dBm]	-95,0
	I/N		[dB]	-49,7
Reflection in the environment				
	Radar Cross section		[m^2]	100
	Distance to "target"		[km]	1
	Both for interferer and interfered radar			
	Reveived power		[dBm]	-145,65
	I/N		[dB]	-50,7

Table 4.13 Interference from FMCW to pulse radar, same frequency.

Interference scenario		**Side lobe on side lobe**		
Interfering radar FMCW				
		Transmit frequency	[MHz]	9410
Lowrance	Shipborne maritime	Signal bandwidth	[MHz]	75
Broadband 3G		Transmit power	[dBW]	-10
		Antenna gain	[dBi]	24
		Side lobe level	[dB]	-25
		EIRP	[dBW/MHz]	-4,8
radiopropagation		distance	[km]	1
		FSA	[dB]	-111,9
Interfered radar pulse				
		Receive frequency	[MHz]	9410
Furuno	Shipborne maritime	Receiver bandwidth	[MHz]	20
FAR 2127		Antenna gain	[dBi]	33,2
		Side lobe level	[dB]	-25
		Noise figure	[dB]	6
		Out of band suppression	[dB]	60
Interference level				
	EIRP interfering radar		[dBW/MHz]	-4,8
	EIRP to interfered radar		[dBW/MHz]	-29,8
	Side lobe -25 dB			
	Propagation loss		[dB]	-111,9
	Antenna gain interfered radar		[dBi]	8,2
	Side lobe -25 dB			
	Received power by interfered radar		[dBW/MHz]	-133,5
			[dBm/MHz]	-103,5
	Received signal bandwidth		[MHz]	20
	Received power in signal bandwidth		[dBm]	-84,7
	Relative sensitivity		[dB]	0,0
	Perceived signal level		[dBm]	-84,7
	receiver noise level		[dBm]	-95,0
	I/N		[dB]	10,3
Reflection in the environment				
	Radar Cross section		[m^2]	100
	Distance to "target"		[km]	1
	Both for interferer and interfered radar			
	Reveived power		[dBm]	-91,446
	I/N		[dB]	3,5

The interference from the FURUNO pulse radar to the Broadband 3G radar is shown in Table 4.14. The values are given for 3.8 km distance, as then an I/N of -6 dB is reached (with the Broadband 3G set to 10 km range[6], interference sensitivity of FMCW is range dependent). Mostly, the side lobe level will be better than -25 dB, so flawless operation is possible for shorter distances. And also this radar will have some desensitization for main lobe on side lobe.

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[6] This radar is inteded for yachts, where mounting is at or below 10 altitude. In this case, the radar horizon is also in the order of 10 km.

Table 4.14 interference from pulse radar to FMCW.

Interference scenario		**Side lobe on side lobe**		
Interfering radar pulse				
		Transmit frequency	[MHz]	9410
Furuno	Shipborne maritime	Signal bandwidth	[MHz]	20
FAR 2127		Transmit power	[dBW]	44
		Antenna gain	[dBi]	33,2
		Side lobe level	[dB]	-25
		EIRP	[dBW/MHz]	64,2
radiopropagation		distance	[km]	3,8
		FSA	[dB]	-123,5
Interfered radar FMCW				
		Receive frequency	[MHz]	9410
Lowrance	Shipborne maritime	Receiver bandwidth	[MHz]	75
Broadband 3G		Antenna gain	[dBi]	24
		Side lobe level	[dB]	-25
		Noise figure	[dB]	6
		Out of band suppression	[dB]	60
Interference level				
	EIRP interfering radar		[dBW/MHz]	64,2
	EIRP to interfered radar		[dBW/MHz]	39,2
	Side lobe -25 dB			
	Propagation loss		[dB]	-123,5
	Antenna gain interfered radar		[dBi]	-1
	Side lobe -25 dB			
	Received power by interfered radar		[dBW/MHz]	-85,3
			[dBm/MHz]	-55,3
	Received signal bandwidth		[MHz]	20
	Received power in signal bandwidth		[dBm]	-42,3
	Relative sensitivity		[dB]	-52,9
	Perceived signal level		[dBm]	-95,2
	receiver noise level		[dBm]	-89,2
	I/N		[dB]	-6,0
Reflection in the environment				
	Radar Cross section		[m^2]	100
	Distance to "target"		[km]	3,8
	Both for interferer and interfered radar			
	Reveived power		[dBm]	-107,8
	I/N		[dB]	-18,5

Analysis of the interference of the FMCW radars ELVIRA and Flex-3D show that frequency separation is sufficient for interference free operation. When using the same frequency, the FMCW radars do interfere pulse and pulse compression radars, as is shown in Table 4.15 and Table 4.16 for pulse radar.

As can be seen, both radars have a high I/N level of 41 and 26 dB, which is substantially more than the interference level of the Broadband 3G radar. Moreover, it is not known whether the ELVIRA and Flex-3D have mitigation techniques like the application of a dead zone.

Pulse and pulse compression radars do NOT have mitigation techniques for FMCW radar.

Table 4.15 Elvira interference to pulse radar.

Interference scenario		**Side lobe on side lobe**		
Interfering radar FMCW				
		Transmit frequency	[MHz]	9410
Robin	Drone detection	Signal bandwidth	[MHz]	50
Elvira		Transmit power	[dBW]	6
		Antenna gain	[dBi]	39
		Side lobe level	[dB]	-25
		EIRP	[dBW/MHz]	28,0
radiopropagation		distance	[km]	1
		FSA	[dB]	-111,9
Interfered radar pulse				
		Receive frequency	[MHz]	9410
Furuno	Shipborne maritime	Receiver bandwidth	[MHz]	20
FAR 2127		Antenna gain	[dBi]	33,2
		Side lobe level	[dB]	-25
		Noise figure	[dB]	6
		Out of band suppression	[dB]	60
Interference level				
	EIRP interfering radar		[dBW/MHz]	28,0
	EIRP to interfered radar		[dBW/MHz]	3,0
	Side lobe -25 dB			
	Propagation loss		[dB]	-111,9
	Antenna gain interfered radar		[dBi]	8,2
	Side lobe -25 dB			
	Received power by interfered radar		[dBW/MHz]	-100,7
			[dBm/MHz]	-70,7
	Received signal bandwidth		[MHz]	20
	Received power in signal bandwidth		[dBm]	-53,7
	Relative sensitivity		[dB]	0,0
	Perceived signal level		[dBm]	-53,7
	receiver noise level		[dBm]	-95,0
	I/N		[dB]	41,3
Reflection in the environment				
	Radar Cross section		[m^2]	100
	Distance to "target"		[km]	1
	Both for interferer and interfered radar			
	Reveived power		[dBm]	-58,685
	I/N		[dB]	36,3

Table 4.16 Flex-3D interference to pulse radar.

Interference scenario		**Side lobe on side lobe**		
Interfering radar FMCW				
		Transmit frequency	[MHz]	9410
Robin	Bird detection	Signal bandwidth	[MHz]	100
Flex-3D		Transmit power	[dBW]	-4
		Antenna gain	[dBi]	33,7
		Side lobe level	[dB]	-25
		EIRP	[dBW/MHz]	9,7
radiopropagation		distance	[km]	1
		FSA	[dB]	-111,9
Interfered radar pulse				
		Receive frequency	[MHz]	9410
Furuno	Shipborne maritime	Receiver bandwidth	[MHz]	20
FAR 2127		Antenna gain	[dBi]	33,2
		Side lobe level	[dB]	-25
		Noise figure	[dB]	6
		Out of band suppression	[dB]	60
Interference level				
	EIRP interfering radar		[dBW/MHz]	9,7
	EIRP to interfered radar		[dBW/MHz]	-15,3
	Side lobe -25 dB			
	Propagation loss		[dB]	-111,9
	Antenna gain interfered radar		[dBi]	8,2
	Side lobe -25 dB			
	Received power by interfered radar		[dBW/MHz]	-119,0
			[dBm/MHz]	-89,0
	Received signal bandwidth		[MHz]	20
	Received power in signal bandwidth		[dBm]	-69,0
	Relative sensitivity		[dB]	0,0
	Perceived signal level		[dBm]	-69,0
	receiver noise level		[dBm]	-95,0
	I/N		[dB]	26,0
Reflection in the environment				
	Radar Cross section		[m^2]	100
	Distance to "target"		[km]	1
	Both for interferer and interfered radar			
	Reveived power		[dBm]	-76,995
	I/N		[dB]	18,0

For ELVIRA and Flex-3D the I/N values are above -6 dB (only if they use the same frequency), as is shown in Table 4.17 and Table 4.18. However for actual side lobe levels, they well might be lower. Moreover, bird radars and drone detection radars usually are located on airports, although bird radars also appear in wind turbines and power substations at sea. In most cases the distance between bird radar and ships will be more than 1 km, so pulse radar interference on FMCW bird radar might not occur often. Moreover, it is unknown whether these radar have pulse radar interference mitigation techniques.

Table 4.17 Pulse radar interference to ELVIRA.

Interference scenario		**Side lobe on side lobe**		
Interfering radar pulse				
		Transmit frequency	[MHz]	9410
Furuno	Shipborne maritime	Signal bandwidth	[MHz]	20
FAR 2127		Transmit power	[dBW]	44
		Antenna gain	[dBi]	33,2
		Side lobe level	[dB]	-25
		EIRP	[dBW/MHz]	64,2
radiopropagation		distance	[km]	1
		FSA	[dB]	-111,9
Interfered radar FMCW				
		Receive frequency	[MHz]	9410
Lowrance	Shipborne maritime	Receiver bandwidth	[MHz]	75
Broadband 3G		Antenna gain	[dBi]	24
		Side lobe level	[dB]	-25
		Noise figure	[dB]	6
		Out of band suppression	[dB]	60
Interference level				
	EIRP interfering radar		[dBW/MHz]	64,2
	EIRP to interfered radar		[dBW/MHz]	39,2
	Side lobe -25 dB			
	Propagation loss		[dB]	-111,9
	Antenna gain interfered radar		[dBi]	-1
	Side lobe -25 dB			
	Received power by interfered radar		[dBW/MHz]	-73,7
			[dBm/MHz]	-43,7
	Received signal bandwidth		[MHz]	20
	Received power in signal bandwidth		[dBm]	-30,7
	Relative sensitivity		[dB]	-52,9
	Perceived signal level		[dBm]	-83,6
	receiver noise level		[dBm]	-89,2
	I/N		[dB]	5,6
Reflection in the environment				
	Radar Cross section		[m^2]	100
	Distance to "target"		[km]	1
	Both for interferer and interfered radar			
	Reveived power		[dBm]	-84,606
	I/N		[dB]	4,6

Table 4.18 Pulse radar interference to Flex-3D.

Interference scenario		**Side lobe on side lobe**		
Interfering radar pulse				
		Transmit frequency	[MHz]	9410
Furuno	Shipborne maritime	Signal bandwidth	[MHz]	20
FAR 2127		Transmit power	[dBW]	44
		Antenna gain	[dBi]	33,2
		Side lobe level	[dB]	-25
		EIRP	[dBW/MHz]	64,2
radiopropagation		distance	[km]	1
		FSA	[dB]	-111,9
Interfered radar FMCW				
		Receive frequency	[MHz]	9410
Robin	Bird detection	Receiver bandwidth	[MHz]	100
Flex-3D		Antenna gain	[dBi]	33,7
		Side lobe level	[dB]	-25
		Noise figure	[dB]	6
		Out of band suppression	[dB]	60
Interference level				
	EIRP interfering radar		[dBW/MHz]	64,2
	EIRP to interfered radar		[dBW/MHz]	39,2
	Side lobe -25 dB			
	Propagation loss		[dB]	-111,9
	Antenna gain interfered radar		[dBi]	8,7
	Side lobe -25 dB			
	Received power by interfered radar		[dBW/MHz]	-64,0
			[dBm/MHz]	-34,0
	Received signal bandwidth		[MHz]	20
	Received power in signal bandwidth		[dBm]	-21,0
	Relative sensitivity		[dB]	-54,0
	Perceived signal level		[dBm]	-75,0
	receiver noise level		[dBm]	-88,0
	I/N		[dB]	13,0
Reflection in the environment				
	Radar Cross section		$[m^2]$	100
	Distance to "target"		[km]	1
	Both for interferer and interfered radar			
	Reveived power		[dBm]	-75,985
	I/N		[dB]	12,0

4.3.4 *Specific case, rainfall radar*

A clearly specific case is the FMCW rainfall rate radar of TUD in the municipality of Rotterdam, as installed on the building “Delftse Poort”.
This radar operates at a frequency assigned to maritime radar and is the only radar in the typical radar list that actually causes an interference problem.

The interference of this radar to a pulse radar is shown in Table 4.19. here the distance is set to 1500 meter, the distance between the Delftse Poort building and the Maas river. The resulting I/N level for the maritime pulse radar is already 39.5 dB, which is effectively blinding or desensitizing the maritime radar.

Note that the level of the second side lobe well could be -25 dB, so the calculation is quite precise in the case we have the main beam “right overhead”. A real main beam on main beam scenario is impossible, the FMCW radar is at 155 m height and tilted upwards by 1.4°.

Note on the antenna tilt of 1.4°:
The Maas river is, at 1500 meter distance, 5.5° down as seen from the radar. Adding the antenna tilt of 1.4°, this implies one is exactly in the "dip" between the second and third side lobe. The second side lobe located up by approx. 35 meter. The radars of small ships are close to the "dip" but the radars of large ships are in the middle of the second side lobe. Moreover, the second side lobe will be closer to the ground at larger distances (actually already around 2 km it is at street level). To reliably judge the interference potential, interfering levels should be evaluated for several heights.

Also the interference caused by the reflection in the environment is critical, Rotterdam has many high-rise buildings that can perfectly act as reflector for the FMCW signal. In many cases, the RCS of the reflector will be well beyond 100 m^2. So even when the main beam is not "pointing in our direction" we well could have high interference levels.

Table 4.19 Interference of rainfall radar to maritime pulse radar.

Interference scenario		**Side lobe on side lobe**		
Interfering radar FMCW				
		Transmit frequency	[MHz]	9410
TUD	Rainfall radar	Signal bandwidth	[MHz]	15
Dedicated		Transmit power	[dBW]	7,4
		Antenna gain	[dBi]	39,3
		Side lobe level	[dB]	-25
		EIRP	[dBW/MHz]	34,9
radiopropagation		distance	[km]	1,5
		FSA	[dB]	-115,4
Interfered radar pulse				
		Receive frequency	[MHz]	9410
Furuno	Shipborne maritime	Receiver bandwidth	[MHz]	20
FAR 2127		Antenna gain	[dBi]	33,2
		Side lobe level	[dB]	-25
		Noise figure	[dB]	6
		Out of band suppression	[dB]	60
Interference level				
	EIRP interfering radar		[dBW/MHz]	34,9
	EIRP to interfered radar		[dBW/MHz]	9,9
	Side lobe -25 dB			
	Propagation loss		[dB]	-115,4
	Antenna gain interfered radar		[dBi]	8,2
	Side lobe -25 dB			
	Received power by interfered radar		[dBW/MHz]	-97,3
			[dBm/MHz]	-67,3
	Received signal bandwidth		[MHz]	15
	Received power in signal bandwidth		[dBm]	-55,5
	Relative sensitivity		[dB]	0,0
	Perceived signal level		[dBm]	-55,5
	receiver noise level		[dBm]	-95,0
	I/N		[dB]	39,5
Reflection in the environment				
	Radar Cross section		[m^2]	100
	Distance to "target"		[km]	1,5
	Both for interferer and interfered radar			
	Reveived power		[dBm]	-60,049
	I/N		[dB]	34,9

A side lobe on main beam is occurring every 2-3 seconds, as is discussed in Section 4.3.1. The resulting levels are shown in Table 4.20. Again, these figures are quite exact with the main beam of the FMCW radar “overhead”. These levels usually “blind the radar” and also well might cause the appearance of a line or bar on the radar screen in the direction of the source radar, located at the Delftse Poort building.

Table 4.20 Interference of rainfall radar to maritime pulse radar, main beam.

Interference scenario		**Side lobe on main beam**		
Interfering radar FMCW				
		Transmit frequency	[MHz]	9410
TUD	Rainfall radar	Signal bandwidth	[MHz]	15
Dedicated		Transmit power	[dBW]	7,4
		Antenna gain	[dBi]	39,3
		Side lobe level	[dB]	-25
		EIRP	[dBW/MHz]	34,9
radiopropagation		distance	[km]	1,5
		FSA	[dB]	-115,4
Interfered radar pulse				
		Receive frequency	[MHz]	9410
Furuno	Shipborne maritime	Receiver bandwidth	[MHz]	20
FAR 2127		Antenna gain	[dBi]	33,2
	Main beam	Side lobe level	[dB]	-25
		Noise figure	[dB]	6
		Out of band suppression	[dB]	60
Interference level				
	EIRP interfering radar		[dBW/MHz]	34,9
	EIRP to interfered radar		[dBW/MHz]	9,9
	Side lobe -25 dB			
	Propagation loss		[dB]	-115,4
	Antenna gain interfered radar		[dBi]	33,2
	Main beam			
	Received power by interfered radar		[dBW/MHz]	-72,3
			[dBm/MHz]	-42,3
	Received signal bandwidth		[MHz]	15
	Received power in signal bandwidth		[dBm]	-30,5
	Relative sensitivity		[dB]	0,0
	Perceived signal level		[dBm]	-30,5
	receiver noise level		[dBm]	-95,0
	I/N		[dB]	64,5
Reflection in the environment				
	Radar Cross section		[m^2]	100
	Distance to "target"		[km]	1,5
	Both for interferer and interfered radar			
	Reveived power		[dBm]	-60,049
	I/N		[dB]	34,9

4.4 Discussion

This discussion is about facts found in the analysis that have broad applicability and that can be used as basis for a planning standard.

Part of this discussion however focuses on specifics of a radar application of a given user, as for example the Robin Flex-3D radar operated by LVNL. These specifics might well be exemplary for a more widespread “misuse” of frequency bands.

4.4.1 General observation

Radars are designed to receive faint reflections from small objects far away. They often employ an extremely large difference between transmit power and receiver sensitivity. Unnecessary to say, these sensitive receivers will also receive interfering radar signals from “nearby”(within line of sight, so not beyond the horizon) radars. This is also confirmed by our analysis. As a consequence, radars rely on mitigation to cancel interference from other radars.

4.4.2 *Mitigation techniques*

As is shown in Section 4.3, radars operating at the same frequency, almost always interfere, and mitigation techniques are indispensable for proper radar operation.

Interference between pulse radars and pulse compression radars[7] is effectively mitigated by using post detection binary integration.

Pulse radars and pulse compression radars do not have mitigation techniques for FMCW radar interference. FMCW radars need to have mitigation techniques for:

- FMCW to pulse (compression) radar interference, as the inclusion of a suitable dead zone (as the broadband 3G radar has).
- FMCW radar – FMCW radar interference, as the use of a variable sweep time (as the broadband 3G radar has).
- Pulse radar to FMCW radar interference, as a band pass filter for only a limited range (which usually all FMCW radars have).

It is strongly recommended to add the use of suitable mitigation techniques as a necessary prerequisite to the permit to use a given radar frequency.

Also frequency separation is a very effective mitigation technique, as is shown in Section 4.3. One easy way of frequency separation can easy be endorsed: let radars use the frequency band dedicated to the application, ATC and drone detection in ATC radar bands, bird radar and rainfall radar in general radar bands[8], etc. Moreover, in the ATC band, with a fixed and relatively limited number of radars, also frequency separation between the various radars can be used.

It is strongly advised to use frequency separation to the maximum extent possible.

4.4.3 *No specific band allocation*

There is no specific allocation for weather radar. Also new applications as bird radar and drone detection radar do not have their own frequency allocation.

All these applications are now considered to be radiolocation devices operating in general radar bands.

A Furuno FAR-6167DS (or alike) is also used as bird radar, the horizontal component of the Robin Flex-3D radar. Currently, the maritime frequency band is used. Although this might be disputable (bird radar is no maritime application) there isn’t a dedicated band for bird radar, moreover it would be difficult to acquire a ship radar in a non-maritime frequency band.

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[7] This includes pulse radar – pulse radar, pulse radar – pulse compression radar and pulse compression radar – pulse compression radar interference.

[8] Meteorological radars are allowed in bands designated to radiolocation (ITU: RLS), being 8500-8750 and 9200-9300 MHz.

Given that maritime S-band radars can operate within each other’s vicinity, it is expected that the use of maritime S-band radars for bird detection does not pose any limitation.

The vertical component of the bird detection radar Flex-3D operates at 9650 MHz, which is a band not allocated for civil radar use.. This also might be disputable, however there is no “bird radar band allocation”.

As discussed earlier, the most effective mitigation technique is frequency separation. As a consequence, the far best solution for radar types that do not have a specific band allocation yet is to allocate a specific band. That would alleviate the frequency management for the ATC band and would relieve the strain on the maritime band. As will be discussed in Section 5.3.3, Germany already has taken this step and has devoted the band below 9 GHz for bird detection radar and drone detection radar.

Harmonizing with Germany also would allow to broaden the floor for this approach and to open up discussion on this topic within ITU (International Telecommunication Union)

4.4.4 *Wrong band allocation*

The Terma 5602, operated by LVNL at Schiphol airport, is a surface movement radar, however operates at 9410 MHz, which is a maritime frequency. According to the ‘Nationaal Frequentieplan 2014’ [1] the band 9000-9200 MHz is meant for ground-based radars with the purpose of aeronautical radio navigation service. This is no technical limitation, the 5602 can be tuned anywhere from 9000 to 9500 MHz.

The current drone detection radar Robin Elvira operates at 9225 MHz (according to license) , which is a maritime radar band[9]. One could argue that drone detection is related to control of the air space and therefore the radar frequency should be in the ATC band.

Also OLC (Obstacle Light Control, lights on wind turbines) is an ATC application that is often operated in the maritime bands, see also section 6.4. OLC is the detection of aircraft, to switch on the obstacle lights. The purpose of the lights is to allow aircraft to navigate around the wind farm. So the radar is used to allow these lights to perform their function and hence the application is clearly Aircraft navigation, for which the band 9000-9200 MHz is allocated. Footnote 5.337 clearly denotes the use of ground based radar for this purpose. Note that the exact location of the aircraft is irrelevant.

4.4.5 *Maritime band*

It appeared that many radars operating under wrong frequency allocation, or no frequency band allocation, use a maritime frequency. Inevitable, the concept of “maritime band = garbage bin band” comes to mind.

Maritime radars are ubiquitous. Almost every cargo ship and every commercial fisherman ship has radar. In addition, many yachts, even small ones, have radar.

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[9] This band is also designated to radio location, so this allocation is in line with the Nationaal Frequentieplan.

The larger cargo ships, and hence their radars, are from all over the world. Control of this use (other than using the dedicated frequency band of 9200-9500 MHz) is difficult and the abundant use of the band provides ample opportunities to mask the operation of a few non-maritime radars, even if they use FMCW without sufficient mitigation techniques.

Only in case of a strong and persistent interferer as the rainfall radar on the Delftse Poort building (Weena 505 Rotterdam), interference becomes so obvious that it can be related to the interferer.

One should note that both sea going maritime traffic and inland shipping have to adhere to safety regulations imposed by IMO (International Maritime Organization) and SOLAS (Safety of Life at Sea). Inland shipping has to adhere to EU directives (Reference [5]) whereas for VTS radars IALA 1111 (Reference [6]) is in charge. All these regulations heavily rely on radar for safety and set minimum requirements for radar performance. Desensitization as can occur by use of FMCW radars (without mitigation) poses a direct risk to safety of maritime traffic.

There well might be applicable law that forbid use of equipment that hampers operation of radars being a safety system, however this is not investigated.

4.4.6 Mitigation in the maritime band

Frequency separation is a good mitigation strategy, however for shipborne radars, this is no option. Location of radars change almost constantly for the vessels being on the move.

Maritime radars rely heavily on their build in mitigation techniques to avoid interference. Pulse radars and pulse compression radars use post detection binary integration. Moreover, solid state radars often can change their operating frequency (to select an interference free frequency). The frequency selection process might even be automated in some radars.

Broadband radars, as for example the Broadband 3G, use a carefully designed dead zone mitigation technique, to both avoid interference between FMCW radars and to avoid interference to pulse radars and pulse compression radars.

It is logical that the “newcomer” FMCW radar has ample mitigation techniques. On one hand, radar manufacturers have to adhere to applicable law. On the other hand, most manufacturers produce pulse radars and pulse compression radars as well, and it is in their own interest that all radars can operate without any interference.

4.4.7 Remarkable FMCW examples

In this paragraph the most striking FMCW examples, seen from interference perspective, are given.

4.4.7.1 Broadband 3G radar

The Broadband 3G radar is a good example of a FMCW radar that has ample mitigation techniques and hence is causing virtually no interference. On one hand, its output power is low (100 mW) and the interference to noise ratio is moderate even at a distance of 1 km, as is shown in Table 4.13.

In addition, the Broadband 3G radar has a well designed dead zone mitigation technique. Its t_{sweep} is too short to cause the post detection binary integration to reach its threshold. The dead zone is long enough to allow for uninterfered operation of pulse and pulse compression radars.

The eminent behaviour of the Broadband 3G radar with respect to interference is no surprise. The radar is designed to operate in an environment where pulse and pulse compression radars are ubiquitous, so interference freedom is necessary. Manufacturers Lowrance, Simrad and B&G also produce pulse compression radars so they have ample knowledge of all radar types and can design mitigation techniques to their optimum performance.

4.4.7.2 *The Weena building FMCW radar*

The analysis given in paragraph 4.3.4 shows that the FMCW rainfall radar is a firm source of interference. Also it was shown that evaluation of the interference level has to take into account the lobes of the antenna, dip and peak of sidelobes are about 35 meter apart (both in azimuth and elevation) at the nearest point of the Maas river. To operate this radar, mitigation techniques are absolutely necessary.

Our research also shows that frequency separation is an effective mitigation technique. So it is questionable why this radar has to operate in the maritime radar band (9300 - 9500 MHz), where these devices should operate in either the 8500 - 8750 MHz or 9200 - 9300 MHz band.

Note that the dead zone mitigation technique might be applied to these radars. However, rainfall radars rely heavily on the emission of energy (the reflection to raindrops is only faint). Dead zone mitigation on the other hand, as is clear from the analysis given in Section 3.5.3, requires a dead zone in the order of 75% of the time, which effectively reduces the emitted energy by a factor of four. For rainfall radar, this could increase the scan time from 1 to 4 minutes. Sufficient frequency separation hence is a far better mitigation strategy.

5 International perspective

5.1 Introduction

This section aims to answer the following research question: How do other European countries deal with the radio planning of radar systems? The focus of this question is restricted to Germany and Belgium, as these countries share borders with the Netherlands. On one hand, the aim of this question is to take stock of the extent to which these countries focus on radio planning for radar systems and to see whether the regulating telecom agencies in those countries even perceive radar-to-radar interference to be an issue of importance. On the other hand, the aim is to check whether the regulating agencies in Belgium and Germany are aware of any cross-border interference issues regarding radar technology.
Both countries are described as separate cases for which we provide a short introduction to sketch the current state in that country. This is followed by a short section on the experiences with radar interferences of the agencies in these respective countries. Thereafter we will shortly describe some specifics about the assignment procedure of these agencies. We then close these cases off by addressing what types of inference mitigation these countries apply.

5.2 Belgium

In Belgium the BIPT (Belgisch Instituut voor Postdiensten en Telecommunicatie) is responsible for the assignment of permits within the telecommunications spectrum. The total number of radar systems deployed in Belgium is estimated in an order of magnitude of dozens. Applications for permits regarding radar technology are handled by the general assignment department of the BIPT. Recently the BIPT has added a new post to this department, which includes a focus on radar permits assignment. Next to military applications, the BIPT categorizes radar applications as aeronautical (Skeyes), maritime or other.

5.2.1 Cases of interference

There are currently no known cases (more specifically: formal complaints) of radar-to-radar interference within Belgium. Most cases concern the interference of WiFi (5 GHz) installations that interfere with radar systems. In general WiFi-equipment is configured to adhere to the frequency plans of a specific country. Yet, equipment bought abroad which hasn't been configured correctly may cause WiFi-installations to interfere with radar systems within the 5 GHz-band.

5.2.2 Assignment procedure

The owner of a radar system has to acquire two permits before he is licensed to use the radar system. One license is needed for the operation of the system, whilst the other is required for the hardware (see Table 5.1 for an overview of the registered parameters). Upon the request for an application of a permit for a civil radar system the BIPT consults with Skeyes, the DGTA (Directorate-General for Air Transport) and the department of Defence on the possibility of conflicts with their systems. A refusal by one of these parties is considered as the leading decision for an application, on the grounds of national or aviation safety.

Table 5.1 Parameters registered per application in Belgium.

Parameter	Unit (if applicable/known)
Permit period	
Contact information	
Number of stations	
Type of station	Basis/Relais/Transportable
Site location - Coordinates - Placement properties - Indoor/Outdoor	
Brand and type of station	
Range	
Preferred frequency	
Direction	Simplex/Duplex
Signal type	Digital/Analogue
Bandwidth	
Channel distance	
Power emitted	In Watts
Elevation from ground	
Antenna type - Omnidirectional - Other properties	
Type of communication	
Region of use	National/Regional/Provincial/Municipal/Local/Aeronautical
Purpose of communication	

5.2.3 *Interference mitigation*

The only form of interference mitigation which is applied, is the aforementioned consultation on interference with military or aeronautical systems. Apart from this assessment, the BIPT does not perform any additional risk assessments on the possibility of interference with other radar systems deployed. Just as in the Netherlands, the BIPT includes a clause on non-interference within their approval of an application. In combination with that, the owner of the radar is brought in contact with Skeyes and the department of Defence, so that the system can be shut down if any problem arises between their systems. Upon application the BIPT records certain parameters on the radar system being applied for (see Table 5.1), yet a complete overview of all radars installed in Belgium does not yet exist; it's development is recently initialised.

5.3 Germany

In Germany the BNetzA (Bundesnetzagentur) monitors and takes care of the practical enforcement of telecommunication regulations. Germany has at least a few hundred civil radar installations. The general assignment department of the BNetzA handles applications. This team includes members with a specific focus on radar techniques.
The German frequency plan includes a singular clear split between military (9.5 to 10 GHz) and civil bands (8.5 to 9.5 GHz) for radar technology, Reference [8], a clear case of frequency separation (as described in Section 3.5.1). If necessary the military is allowed to operate in the civil band as well after consultation with the civil parties. But once the military takes a decision regarding their designated bands,

their decision is leading. Next to that, the BNetzA has also reserved specific bands for specific applications of radar technology.

5.3.1 *Cases of interference*

Weather radars in Germany appeared to interfere with each other in the past. This was solved by synchronization of all weather radar systems to prevent a direct line of sight. As these systems were all operated by the same organization, this solution was easy to coordinate. When different parties are involved, synchronization might prove more difficult to set up and a solution as sector blanking might be more suitable (see Section 3.5.6)

There have been no clear examples of cross-border interference between Germany and the Netherlands. In most cases, especially with the 9 GHz radars, there is enough geographical separation between the systems across borders. The BNetzA did experience some problems at the French border regarding weather radars running at 5.6 GHz. This was mainly caused by radar systems having been deployed on hills on either sides of the border. In that case interference occurred with radars which were even at a distance of 150 km form one another. Such a situation could only be solved if both sides cooperated in the placement of filters on their systems.

Next to the cases of radar-to-radar interference, Germany also has cases of radar interference with WLAN-systems and radio astronomy.

5.3.2 *Assignment procedure*

For their band plan and assignment procedure the BNetzA refers to the ITU and ETSI standards. In order to apply for a permit in Germany the owner of the radar system has to submit a form containing the specifics on the system. In practice the BNetzA has a list of civil radars with frequencies, power and location (see Table 5.2 for the specific parameters). With every new application a geographical analysis is performed to predict interference. This is mainly calculated through line-of-sight in combination with ground elevation data. Another factor to consider in this analysis is the probability of two radar systems being in line of sight of one another. When the BNetzA is not sure on whether a system that is being applied for will suffer from interference, a trial license will be granted. If, thereafter, interference is detected within these systems the owners of the system can discuss on a solution among each other.

The most prominent problem for the BNetzA regarding the assignment of frequency for radar systems lies in the lack of insight on the receiving side. On this receiving side the systems apply signal processing, which can effectively reduce the effect that interference has on the system. As the BNetzA has no sight on which radar installation uses which kind of signal processing, it is difficult for them to guarantee a certain standard of quality for the spectrum that they assign to radar systems.

Another hurdle for the BNetzA is the lack of information on the internal workings of specific radar systems. Radar suppliers rarely share the specifics of their systems. This leaves the BNetzA less well equipped in their analyses for possible interferences.

Table 5.2 Parameters registered per application in Germany.

Parameter	**Unit (if applicable/known)**
Contact information	
Purpose of communication	
Preferred frequency	
Site location - Coordinates - Elevation (above ground and above sea level)	
Brand/type antenna	
Brand/type transmitter	
Duty cycle	%
Transmitter output peak power	MW
Bandwidth	MHz
Smallest pulse width modulation envelope	μs
Feed loss	dB
Equivalents isotropic radiated power (EIRP)	MW
Antenna gain	dBi
Horizontal and vertical opening angle of the antenna	°
Polarization	Vertical/horizontal/circular
Send type	
Minimum rise / fall time of the modulation envelope	ns
Azimuth of main beam direction	°
Elevation of the main beam direction	°
Antenna type	Omnidirectional / directional (fixed/rotating)

5.3.3 *Interference mitigation*

In Germany, a number of mitigation strategies is being deployed. One method of reducing interference is by separating the bands assigned for radar by their application. The BNetzA has recently seen an increasing demand in applications for drone detection radars, therefore this application, together with bird detection radars, have been relocated to below the 9 GHz band. This could suit the situation well, since there were only a few radar applications registered to operate below 9 GHz. This, however, didn’t suit the suppliers of radar equipment, as they had to modify their product for them to operate below 9 GHz. Nonetheless, this year the first radar systems using that frequency range have been produced by these suppliers. In the past Germany has used a lot of its available space to install wind farms. This increase the demand for radars that are used for aircraft detection. Considering this demand as well, the BNetzA thought it best to keep these systems in separate ranges from the bird and drone detection radars.

As of this year Germany has also been able to offload this demand for aircraft detection systems to the frequency range between 1040 and 1090 MHz, which is originally used for air traffic control. It is now allowed to implement detection systems which receive transponder-transmissions of aircrafts in order to predict their flight route. Sending request-signals on 1030 MHz is not allowed though.

Different radar technologies that exists allow for systems that suffer less from interference or induce less interference. Therefore, the BNetzA discussed the possibility of allowing only certain types of radars on specific ranges of the spectrum, but no conclusion has been reached on this point yet.

6 Response to Research Questions

This chapter provides an answer to the research questions as given in Section 1.2.

In short, the following research questions were given.

- Need for planning criteria:
  - Substantiation,
  - Planning criteria,
  - Performance criteria.
- Generic standard.
- Planning criteria per category.
- Radar developments.
- International comparison.

These questions will be answered in the next sections.

6.1 Need for planning criteria

Question:
Is there a general need to adhere to planning criteria when granting a license for a radar system?

Answer:
The short answer: yes

There is a general need to adhere to planning criteria when granting a license for a radar system. However, there is some differentiation in the answer.

In general, planning criteria results in good frequency management which provides frequency separation between the radars, thereby effectively mitigating interference. Frequencies can be re-used by a radar that is beyond the horizon.

Planning criteria are eminent for ATC radars, where safety and hence interference free operation is of prime importance. Criteria can be easily applied, given that radar locations are known and only a moderate number of radars are used.

It is also advised to operate drone detection radars in (a specific part of) the ATC band (9000 - 9200 MHz). These are FMCW radars that usually do not apply dead zone mitigation, so frequency separation with pulse and pulse compression radars is necessary and this can be accomplished in the “planned” ATC band. This band might get “overcrowded”, so one could allocate only a part of this band for drone detection. The German approach, to locate the band below 9 GHz for drone and bird detection, would also be advisable, should it be possible given the current allocation.

Frequency separation is impossible in the maritime band, given that radars move and come from all over the world. The planning criterion in the maritime band could be: allow only maritime radars in this band, that apply all necessary mitigation techniques. Especially dead zone mitigation shall be endorsed for all FMCW radars.

Weather radars and especially FMCW weather radars shall be allowed only in the band for meteorological research. They do not have any mitigation technique and they pose a high interference risk to either maritime or ATC radar.

In summary:
- In the maritime band: only allow maritime radars. They have sufficient mitigation techniques.
- In the ATC band: use frequency planning and re-use frequencies only under “beyond horizon’ conditions. (Note that the higher the antenna, the farther the horizon).
- Allow only weather radars in general radar bands.
- Bird detection: can be operated in either ATC or in maritime band, however they shall adhere to the regulations in that band (need a specific frequency allocation in ATC band, or use a standard maritime radar in the maritime band).

6.1.1 Substantiation

Question:
If there is no general need to adhere to planning criteria, what is the (preferably also numerical) substantiation for this?

Answer:
There is a need to adhere to planning criteria, and the substantiation has been given in Section 4.3 and 4.4.

6.1.2 Planning criteria

Question:
If there is a general need to adhere to planning criteria, what are these planning criteria, taking into account the performance criteria of the different radar systems? Given that parameters such as central frequency, bandwidth, transmission power (in EIRP), modulation shape, antenna height, antenna direction and location are determined.

Answer:
The planning criteria are:
- Maritime bands: only allow maritime radars in this band.
- ATC bands: create frequency separation between the ATC radars. Re-use of frequency is allowed under “over the horizon” conditions.
- Weather radars in the band for meteorological research.

The relevant radar parameters are:
- For radars in the ATC band:
  - Central transmit frequency,
  - Bandwidth,
  - Antenna height (for over the horizon determination),
  - Location (for over the horizon determination).
- For radars in the maritime band:
  - Modulation shape
    More specific: sweep time (or pulse length) and dead zone (to evaluate dead zone mitigation).

6.1.3 Performance criteria

Question:
What are the desired / required performance criteria of radars in this respect and can these be translated into concrete protection criteria that must be incorporated in the radio planning and that are reflected in the aforementioned parameters?

Answer:
The radars have to adhere to the following performance criteria:

- Pulse radars and pulse compression radars shall have at least post detection binary integration as mitigation technique.
- FMCW radars shall employ a suitable dead zone mitigation technique.
- Radars shall have a wide dynamic range of at least 100 dB.
- Radars shall have sufficient band-stop attenuation (preferably at least 80 dB).
- Preferably, radars shall have an adjustable transmit frequency.
- Preferably, the adjustable transmit frequency shall be set and changed automatically.

6.2 Generic standard

Question:
Is there a generic standard or value to be applied or a substantiated rule of thumb?

Answer:
The generic standard is:

- Radars shall adhere to the performance criteria in Section 6.1.3.
- Planning criteria of Section 6.1.2 shall be used.

Especially for the maritime domain, the mentioned mitigation techniques shall be endorsed.

Our analysis is based on “typical” radars. Most radars in the market resemble one of these radars. If a radar has different performance parameters, especially if it uses much higher EIRP, or a far larger modulation bandwidth, or a totally different modulation scheme, then it is advised to repeat the calculations in this document for that radar.

6.3 Planning criteria per category

Question:
If a generic standard or rule of thumb is possible and useful, what are the (planning) criteria to be applied per category?

Answer:
The planning criteria are:

- Maritime bands: only allow maritime radars in this band.
- ATC bands: create frequency separation between the ATC radars. Re-use of frequency is allowed under “over the horizon” conditions.
- Weather radars in the band for meteorological research.

6.4 Radar developments

Question:
What are the developments with regard to radar applications and systems and what consequences can this have for radio planning and the possible exclusion or facilitation of new and certain types of radar systems?

Answer:
Developments with respect to applications.
Especially for the air domain, interest is shifting from “only aircraft” to “anything in the air”. This has as consequence that there is a sharp increase for radars that can track birds, drones and aerosols, dust, water vapor, rain, hail, snow and alike.

The consequence for radio planning: all these new applications need frequency space. For meteorological research, this frequency space is already reserved, which is a virtue given that these radars need very high powers to detect and measure speed of the low reflecting aerosols, dust, water vapor, rain, hail, snow and alike. The interference potential of these radars is high.

“New kid on the block” is the FMCW radar. These radars have low transmit powers, allowing use of solid state technology, which in turn allows for easy adaptation of the transmit frequency. FMCW radars have a high interference potential, in ATC and maritime bands these radars shall not be allowed without suitable mitigation techniques.

Modern radars profit from the vast developments in digital technology. Even low end yacht radars, as for example the Lowrance Halo20 dome radar comes with pulse modulation schemes previously found on multi-million ATC radars. More and more, radars will use pulse compression and also have the flexibility to adjust their transmit frequency. This flexibility can be used for planning in the ATC band, a specific frequency can be imposed.

Currently, application of bird detection and drone detection is not explicitly mentioned in frequency planning. If they use the maritime or ATC bands, these radars shall adhere to the applicable requirements in this band with respect to mitigation techniques and frequency use.

Radar is also used for Obstacle Light Control (OLC, turn light on only if there is air traffic in the neighbourhood). Although an ATC application (monitoring of air traffic), these radars are often operated in maritime frequency bands. Operation however shall be in the ATC bands, where frequency management is present and interference free operation can be guaranteed.
Note that only proper detection is a requirement. OLC does not require accuracy, nor are there stringent requirements for false alarm rate. So advanced radars can be omitted, or used in a less-high-performing mode.
Note that obstacle lights and hence OLC is a safety feature.

6.5 International comparison

Question:
How do other European countries deal with the radio planning of radars? Emphasis is placed on the neighbouring countries Germany and Belgium, taking into account the possibly required notification and coordination of frequency use between countries.

Answer:
Germany and Belgium recognise the problem of radar interference. This number of known cases (formal complaints) is still quite low, but an increase is expected as a result in the growing number of radar applications. The radio planning practices are quite similar to the Dutch situation, although the BNetzA seems to register a greater number of parameters for each applicant.

The agencies currently deal with interference in the following ways:
- **Germany** – strong(er) separation between civil and military use (being a form of frequency separation), lowering demand for national radar applications (see the example using transponder data for aviation detection) and a case by case approach (e.g. weather radar synchronisation).
- **Belgium** – consultation on interference with military or aeronautical systems. Apart from this assessment, the BIPT does not perform any additional risk assessments on the possibility of interference with other radar systems deployed. Just as in the Netherlands, the BIPT includes a clause on non-interference within their approval of an application.

7 Conclusions and recommendations

7.1 Conclusions

The following can be concluded from this document:

1. Radars do have sensitive receivers and are sensitive to interference from other radars. Interference mitigation techniques are necessary.

2. Frequency separation is an effective mitigation technique.

3. FMCW radars are gaining popularity for all types of applications.

4. FMCW radars need mitigation techniques to I) being interfered by other (FMCW) radars and II) to cause interference tot pulse and pulse compression radars.

5. Many new radar application areas arise, as drone detection, bird detection, rainfall measurement, obstacle light control etc…

6. The maritime radar band is incorrectly used by numerous “non-maritime” radars.

7. Germany and Belgium recognise the issue of radar interference, but have a limited number of known cases (formal complaints). When compared to the Netherland, they apply highly similar radio planning practices.

7.2 Recommendations

The following recommendations are made:

1. It is strongly recommended to add the use of suitable mitigation techniques as a necessary prerequisite to the permit to use a given radar frequency, to enhance efficient use of the available frequency space.

2. Use planning criteria in the maritime bands: Only allow maritime radars in this band.

3. Use planning criteria in the ATC bands: apply frequency management. Create frequency separation between the ATC radars. Re-use of frequency is allowed under “over the horizon” conditions.

4. For weather radar and rainfall rate radar: use the meteorological research band.

5. For radar applications not having their own frequency band allocation: if they use the maritime or ATC frequency bands, those radars have to adhere to the applicable planning criteria in that band, especially with respect to interference mitigation techniques.

6 In order to better apply planning criteria, it is advised to have mentioned in the broadcasting license the following parameters:
   - Radar type (FMCW, pulse / pulse compression),
   - Transmit power,
   - Antenna gain,
   - Antenna beam width, both horizontal and vertical,
   - Antenna tilt,
   - Gain in first side lobe,
   - Radiated power (EIRP),
   - Antenna polarization,
   - Duty cycle,
   - Pulse length/sweep time,
   - Dead zone,
   - Pulse repetition frequency,
   - Mitigation techniques applied in the transmitter.

7 Actively share experiences and (new) working practices with the radiocommunication agencies of Belgium and Germany, starting with the findings of this report.

8 To create a proper frequency separation between maritime and ATC radar on one hand and new radar types for detection of birds and drones on the other, it is advised to assign separate frequency bands to bird and drone detection radar.
Following the German initiative (allocation of the band below 9 GHz) would facilitate harmonization and would open the floor to discuss this designation also at ITU.

9 It is strongly recommended to add the use of suitable mitigation techniques as a necessary prerequisite to the permit to use a given radar frequency.

8 Abbreviations and symbols

8.1 Abbreviations

AT	Agentschap Telecom (Dutch for: Radiocommunications Agency)
ATC	Air Traffic Control
CARPET	Computer Aided Radar Performance Evaluation Tool
CFAR	Constant false Alarm Rate
CW	Continuous Wave
dBi	dB relative to an isotropic radiator
dBm	dB relative to milliWatt
dBW	dB relative to Watt
EIRP	Effective Isotropic Radiated Power
EU	European Union
FM	Frequency Modulation
FMCW	Frequency Modulated Continuous Wave
FSA	Free Space Attenuation
GPS	Global Positioning System
IALA	International Association of Marine Aids to Navigation and Lighthouse Authorities (previously known as International Association of Lighthouse Authorities)
ILS	Instrument Landing System
IMO	International Maritime Organisation
I/N	Interference to Noise ratio
ITU	International Telecommunication Union
OLC	Obstacle Light Control
PCR	Pulse Compression ratio
PRF	Pulse Repetition Frequency
PRI	Pulse Repetition Interval
RLS	Radio Location Services
RNAV	Area Navigation
RNP	Required Navigation Performance
RCS	Radar Cross Section
S-band	Frequency band 2-4 GHz
SOLAS	Safety of Life at Sea
STC	Sensitivity Time Control
TERPEM	Terrain Parabolic Equation Model
TNO	Nederlandse Organisatie voor Toegepast Natuurwetenschappelijk Onderzoek (Dutch for: Netherlands organisation for applied scientific research)
VTS	Vessel Traffic Service
X-band	Frequency band 8-12 GHz

8.2 Symbols

c	Speed of light, [m/s], about 3*10^8 m/s.
Δf	Frequency difference between transmitted and received signal [Hz]
f_{max}	Maximum frequency difference between transmitted and received signal [Hz]
G	Antenna gain
G_A	Antenna gain (main lobe gain)
G_R	Receive antenna gain
G_{sla}	Absolute side lobe gain
G_T	Transmit antenna gain
λ	Wavelength of the radar signal [m]
P_r	Received power [W]
P_t	Transmitted power [W]
R	Range [m]
R_{max}	Maximum range [m]
R_r	Range (or distance) from receiver to target [m]
R_t	Range (or distance) from transmitter to target [m]
$R_{th.max}$	Theoretical maximum range [m]
σ	Radar cross section (RCS) [m^2]
S_{rel}	Relative sensitivity
t	Time [s]
t_{rep}	*Repetition time [s]*
t_{sweep}	Sweep time (of FMCW) [s]
t_p	Pulse length [s]
f_{rep}	Repetition frequency

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10 Signature

The Hague, October 2020	TNO Electronic Defence
P.W.L. Weimar Research manager	O. van Gent Author

A Typical radar systems used in the study

Brand/ type	Description	Waveform	Frequency (MHz)	Receiver bandwidth (MHz)	Sweep bandwidth (MHz)	Transmit power (dBW)	Antenna gain (dBi)	EIRP (dBW)	Beamwidth	Pulse width	Pulse repetion frequency
THALES Star2000	Air surveillance radar	pulscompr	2895	2	2	44,8	34,3	79,1	2,4°	98 µs	1,1 kHz
Furuno FAR-6167DS	Shipborne maritime Similar in Flex-3D	puls	3050	30		47,8	26,8	74,6	1,8°*25°	80 ns	1,9 kHz
Furuno FAR 2127	Shipborne maritime	puls	9410	3-20-40		44	33,2	77,2	0,95°*20°	0,07-1,2 µs	600-3000 Hz
Lowrance Broadband 3G	Shipborne maritime	FMCW	9300-9400	75	75	-10	24	14	5,2°*25°	1,3 ms	200 Hz
Terma Scanter 5200	Land based maritime VTS	pulscompr	9000-9200 or 9225-9500	40	40	23	38	61	0,36°*13°	100 µs	1 kHz
Terma Scanter 5602	Airport Surface movement	pulscomp	9410	40	40	23	35	58	0,7°*13°	100 µs	1 kHz
Robin Flex-3D	Bird detection	FMCW	9650	100	100	-4	33,7	29,7	0,8°*20°	Unknown	Unknown
Robin Elvira	Drone detection	FMCW	9250	50	50	6	39	45	2,1*2,1	Unknown	Unknown
TUD	Rainfall radar	FMCW	9200-9500	7,5-50	7,5-50	7,4	39,3	46,7	2,1 * 2,1	Unknown	Unknown