ECC Report 351

UWB radiodetermination applications within the frequency range 116 GHz to 148.5 GHz for vehicular use

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0 EXECUTIVE SUMMARY

0.1 EXTERIOR VEHICULAR RADAR

0.1.1 Radio Astronomy

A single-interferer scenario compatibility study between Radio Astronomy Service (RAS) and radiodetermination devices for exterior vehicular radar has been conducted.

The study shows that separation distances are needed between the short-range devices and the observatories of NOEMA in France and IRAM 30 m in Spain in order to protect the RAS. These separation distances are dependent on the frequency and on the e.i.r.p. of the interfering short-range devices. The effectual mean e.i.r.p. of the SRDs which has been considered for this single-interferer study were 9 and 32 dBm in a bandwidth of 8 GHz, corresponding to the maximum power levels of corner and short/ultra-short radars, or front radars, respectively.

The study shows that separation distances around the radio astronomy sites of NOEMA in France for a maximum allowed mean e.i.r.p. level of 32 dBm in a bandwidth of 8 GHz, and IRAM 30 m in Spain for e.i.r.p. levels of 9 and 32 dBm in a bandwidth of 8 GHz have to be respected for the emissions of the radio determination devices for exterior vehicular radar.

An implementation of an automatic system to disable the transmission of the short-range device coupled with geo-positioning of the vehicle, referred to as “exclusion zone”, should be considered in order to protect the immediate vicinity (e.g. 3 km radius) of each RAS site.

An implementation of an automatic system to adapt the transmission parameters of the short-range device coupled with geo-positioning of the vehicle, referred to as “coordination zone”, should be considered in order to overcome compatibility issues. Several proposals for the definition of coordination zones are provided in ANNEX 3 for both NOEMA in France and IRAM 30 m in Spain. For the NOEMA site, the coordination zones design Option 4 is the recommended approach, as illustrated by Figure 19. For the IRAM 30 m site, the coordination zones design Option 3 is the recommended approach, as illustrated by Figure 20.

Although no aggregated studies were performed, it was expected that single entry studies provide a reasonable approximation.

0.1.2 Fixed Service

The single entry interference studies show that operation in the bands adjacent to fixed service is possible provided that the mean power densities in the fixed service bands are at most -33 dBm/MHz e.i.r.p. for the front radars and -36 dBm/MHz e.i.r.p. for the corner and short/ultra-short range radars. The corresponding peak power levels are 2 dBm e.i.r.p. within 1 GHz for the front radars and -1 dBm e.i.r.p. within 1 GHz for the corner and short/ultra-short range radars.

Co-channel operation in the 141-148.5 GHz band between the exterior vehicular radars and fixed services is only possible provided that the mean power densities are at most -33 dBm/MHz e.i.r.p. for the front radars and -36 dBm/MHz e.i.r.p. for the corner and short/ultra-short range radars. The corresponding peak power levels are 2 dBm e.i.r.p. within 1 GHz for the front radars and -1 dBm e.i.r.p. within 1 GHz for the corner and short/ultra-short range radars.

0.1.3 Earth Exploration Satellite Service (Passive)

For all investigated frequency ranges, the EESS (passive) protection criterion is satisfied for the considered aggregate scenarios, for any radar types, including aggregation of all radar types. Such results can be observed in Table 25, Table 26 and Table 27, as they exhibit positive margins. Under the assumed technical parameters defined in section 5.1, and the interference scenarios defined in section 5.2.3, it is concluded that compatibility of exterior vehicular radar can be ensured with EESS (passive).

Additional calculations have shown that a protection level of -49 dBm/MHz is required for the MWI system in the 116-122.25 GHz band as the most stringent requirement, while protection of system N1 outer in the 141 - 148.5 GHz band requires a protection level of -43.5 dBm/MHz.

Finally, in section 5.3.4, a proposal for limiting radars' unwanted emissions towards the EESS bands is provided, intending to regulate maximum transmit power in the unwanted emissions domain and antenna directivity to ensure compatibility with EESS in the adjacent bands, for radars operating in the 122.25-130 GHz band and for radars operating in the 134-148.5 GHz band.

0.1.4 Amateur and Amateur-Satellite Services

For front EVR, MCL calculations reveal main beam to main beam separation distances of up to 14.5 km, but this does not take into account the possible vertical and horizontal separation, as well as clutter/shielding. Introducing 100 m of vertical separation into the same calculation, the distance reduces to 5.4 km. With 300 m of vertical separation, which may be difficult to achieve, the distance reduces to 0 km.

For corner or short/ultra-short EVR, MCL calculations reveal main beam to main beam separation distances of up to 4.6 km, but this does not take into account the possible vertical and horizontal separation, as well as clutter/shielding. With 100 m of vertical separation, the distance reduces to 0 km.

In general, the separation distance depends highly on transmission power level and angular offset (elevation and azimuth) between the vehicular radar transmitter to the amateur radio receiver. Due to the use of directive antennas the areas where interference to the amateur radio receiver would be higher than the protection criteria (-6 dB I/N) are limited to a small angle around amateur radio receiver's azimuthal directivity.

However, given the typical deployments of amateur stations in this frequency range, a critical and persistent worst-case alignment with the external vehicle radars is highly unlikely, due to natural mitigating factors such as:

- Road traffic has to be inside of the relatively narrow interference area;
- The car's antenna must be directed towards the amateur station antenna;
- LOS conditions between EVR and the amateur station receiver must apply;
- Vertical separation between the amateur station location and the vehicle radars reduces the impact;
- Typical duty cycles (50%) and frequency hopping techniques (effective additional DC factor of 25%) used by front-radars with high antenna gain, low bandwidth reduce the average interference into the amateur receiver. This may significantly reduce the impact on many amateur applications;
- Calculations are representative of a static situation whereas in a real dynamic situation, any potential interference will not be present all time.

Therefore, potential interference from external vehicular radars to the Amateur Service seems to be negligible in the bands 122.25-123 GHz and 134-141 GHz.

For the Amateur-Satellite Service operations, the antenna would be tilted skyward in which case the separation distances would be very much reduced due to side lobe coupling from the directional amateur station antenna. No specific studies of this scenario were deemed necessary.

Thus, it is concluded that in the bands 122.25-123 GHz and 134-141 GHz, coexistence between external vehicular radars and the Amateur and Amateur-Satellite Services can be achieved.

0.1.5 Summary

The following conditions need to be fulfilled for coexistence:

- In the band 116-122.25 GHz, EESS (passive) band, compatibility with EESS (passive) determines the allowable unwanted emissions, up to -50 dBm/MHz mean e.i.r.p. density and -76 dBm/MHz maximum e.i.r.p. density above 35 degrees elevation for duty cycles ≤50%, and up to -53 dBm/MHz mean e.i.r.p. density and -79 dBm/MHz maximum e.i.r.p. density above 35 degrees elevation for duty cycles >50%;
- In the bands 122.25-130 GHz and 134-141 GHz, sharing with RAS determines the operating conditions. Outside the coordination and exclusion zones, front radars can have a mean e.i.r.p up to 32 dBm in a

bandwidth of 8 GHz, while corner and short/ultra-short range radars can have up to 9 dBm mean e.i.r.p. in 8 GHz.

Between 130-134 GHz, compatibility with fixed services is the most critical. This is possible with:
- Maximum mean power spectral density of -33 dBm/MHz e.i.r.p. for the front radars;
- Maximum mean power spectral density of -36 dBm/MHz e.i.r.p. for the corner and short/ultra-short range radar.

In the band 141-148.5 GHz, sharing with fixed services determines the operating conditions. The maximum wanted emissions requirements for all types of radar are:
- a maximum power spectral density (PSD) of -36 dBm/MHz e.i.r.p.;
- -6 dBm mean e.i.r.p. within 1 GHz;
- -1 dBm peak e.i.r.p. within 1 GHz.

Finally, for the band 148.5-151 GHz, compatibility with EESS (passive) determines the allowable out-of-band emissions, up to -44 dBm/MHz mean e.i.r.p. density and up to -70 dBm/MHz mean e.i.r.p. density above 35 degrees elevation for duty cycles ≤50%, and up to -47 dBm/MHz mean e.i.r.p. density and up to -73 dBm/MHz mean e.i.r.p. density above 35 degrees elevation for duty cycles >50%.

0.2 IN-CABIN VEHICULAR RADAR

0.2.1 Radio Astronomy

A single interferer scenario compatibility study between Radio Astronomy Service and in-cabin radar was conducted.

The calculated regions of zero margin for RAS stations IRAM 30 m in Spain and NOEMA in France are very limited and include only direct vicinity of both radio stations. No public roads or residential areas are located within the zero margin areas. However, in order to ensure protection of RAS stations it is proposed to define an exclusion zone in direct vicinity of each of radio station.

Radio telescope community indicated the need to protect the immediate vicinity (e.g. 3 km radius around the RAS) of both telescopes with a very stringent power limit (ideally a switch-off), since it is possible that people would drive cars up to the telescope even in absence of public roads or bring cars up to the RAS using cable car.

An implementation of an automatic system to disable transmission of in-cabin radar devices coupled with geo-positioning of the vehicle, referred as “exclusion zone”, should be considered in order to protect immediate vicinity of each RAS station. An exclusion zone is defined as a geographical area (typically the area within a circle with e.g. 3 km radius) within which the transmit operation of the radar equipment is automatically disabled (without manual intervention from the driver of the vehicle) to ensure no disturbance is generated towards a RAS in immediate vicinity.

The study showed that additional separation distances, beside exclusion zones in direct vicinity of RAS stations, are not needed between in-cabin vehicular radar and observatories NOEMA in France and IRAM 30 m in Spain.

Although no aggregated studies were performed, it was expected that single entry studies provide a reasonable approximation of a worst-case scenario.

0.2.2 Fixed Service

The single entry interference studies show that sharing between in-cabin vehicular radars and fixed services is possible for the considered in-band power level of 3 dBm mean e.i.r.p. and 16 dBm peak e.i.r.p. within a bandwidth of 1 GHz. For adjacent band compatibility studies, a 20 dB out-of-band attenuation was assumed, leading to -17 dBm mean e.i.r.p. and -4 peak e.i.r.p. in 1 GHz and hence showing compatibility.

0.2.3 Earth Exploration Satellite Service (Passive)

Results of the studies show that, for both single entry and aggregated interference scenarios, the protection of the EESS (passive) would be ensured for in-cabin radar operating in the adjacent frequency bands 122.25 - 130 GHz and 141-148.5 GHz. On the other hand, the case of the protection of the EESS (passive) from in-cabin radar operating co-frequency in the frequency band 116-130 GHz depicts large negative margins for aggregated study for the band 116-122.25 GHz.

No mitigation technique has been determined that could be considered to ensure the protection of EESS from in-cabin radar in the aggregated effect in the 116-122.25 GHz band. Therefore, the coexistence cannot be ensured with in-cabin radars.

For in-cabin radar working in frequency bands 122.25-130 GHz and 134-148.5 GHz, the following technical conditions could apply (on per radar basis).Band 122.25-130 GHz:

- Maximum (mean) e.i.r.p. density in adjacent (EESS) band 116-122.25 GHz: -45 dBm/MHz;
- Downwards antenna orientation;
- Report shows that sensors integrated in conventional cars or cars with sunroof ensure at least 15 dB of exit-loss (attenuation) from the radar main beam to the EESS (passive) sensors' directions. In other cases, e.g. convertible cars, the minimum of 15 dB exit-loss (in worst case) needs to be proven. Process of proving is to be specified and agreed.

Band 134-148.5 GHz:

- Maximum (mean) e.i.r.p. density in adjacent (EESS) band 148.5-151 GHz: -39 dBm/MHz;
- Downwards antenna orientation;
- Report shows that sensors integrated in conventional cars or cars with sunroof ensure at least 15 dB of exit-loss (attenuation) from the radar main beam to the EESS (passive) sensors' directions. In other cases, e.g. convertible cars, the minimum of 15 dB exit-loss (in worst case) needs to be proven. Process of proving is to be specified and agreed.

0.2.4 Amateur and Amateur-Satellite Services

For in-cabin vehicular radars no interference could be found due to the low level of emissions and the body attenuation of the vehicle.

Thus, it is concluded that in the bands 122.25-123 GHz and 134-141 GHz, coexistence between in-cabin vehicular radars and the Amateur and Amateur-Satellite Services can be achieved.

0.2.5 Summary

The following conditions need to be fulfilled for coexistence.

For the in-cabin vehicular radar, the candidate frequency bands 116-130 GHz, 134-141 GHz and 141 - 148.5 GHz have been studied. The result of the studies showed that compatibility between in-cabin radar and investigated services in frequencies 122.25-130 GHz, 134-141 GHz and 141-148.5 GHz can be ensured under the technical assumptions used in the studies. In the light of this results of the studies it is likely that the 134-148.5 GHz range can be considered as a single band since all assumptions used and the calculations made for 134-141 GHz and 141-148.5 GHz bands are same.

In most frequency bands, EESS (passive) is the critical service determining the conditions under which compatibility is possible. In the bands 122.25-130 and 134-148.5 GHz that implies:

- Downwards antenna orientation;
- "15 dB exit loss" from the radar main beam to the EESS (passive) sensors' directions;
- Maximum mean e.i.r.p density -30 dBm/MHz;
- Maximum mean e.i.r.p. 3 dBm over the bandwidth;
- Maximum peak e.i.r.p. 16 dBm over the bandwidth;
- Minimum 1 GHz bandwidth.

In the EESS (passive) band 116-122.25 GHz, radars´ unwanted emissions should stay below a maximum. mean e.i.r.p density. of -45 dBm/MHz and in the EESS (passive) band 148.5-151 GHz below -39 dBm/MHz.

In the 130-134 GHz band, only 20 dB out-of-band attenuation is required, corresponding to a maximum unwanted emission level of -17 dBm/GHz.

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LIST OF ABBREVIATIONS

Abbreviation	Explanation
ALMA	Atacama Large Millimeter/submillimeter Array
ADAS	Advanced Driver-Assistance Systems
ASML	Above mean sea level
BEL	Building Entry Loss
BW	Bandwidth
BWA	Broadband Wireless Access
CEPT	European Conference of Postal and Telecommunications Administrations
CO	Continuous observation
DATV	Digital Amateur TV
ECA	European Common allocation
ECC	Electronic Communications Committee
EESS	Earth Exploration Satellite Service
e.i.r.p.	Equivalent Isotropically Radiated Power
ETSI	European Telecommunications Standards Institute
ESA	European Space Agency
Euro NCAP	European New Car Assessment Programme
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
EVR	Exterior vehicular radar
FMCW	Frequency Modulated Continuous Wave
FS	Fixed Service
FWA	Fixed Wireless Access
IF	Intermediate Frequency
IFOV	Instantaneous Field of View
LOS	Line of Sight
MCL	Minimum Coupling Loss
MIMO	Multiple Input Multiple Output
NLOS	Non-Line of Sight
OFDM	Orthogonal Frequency-Division Multiplexing
OFR	Operating frequency range
OOB	Out-of-band
OOBE	Out-of-band emissions
PP	Point-to-Point

Abbreviation	Explanation
PSD	Power spectral density
RCS	Radar Cross Section
RAS	Radio Astronomy Service
RF	Radio Frequency
RX	Receiver
SLO	Spectral line observation
SRD	Short range device
TX	Transmitter
UWB	Ultra-Wideband
VLBI	Very-Long Baseline Interferometry

1 INTRODUCTION

This Report addresses next generation vehicular UWB radiodetermination applications operating in the 116 to 148.5 GHz range.

It is envisaged that this frequency band can support future autonomous driving applications. These radars could be used to support features like automatic cruise control, lane keep, lane change assist or automatic emergency braking. To enable autonomous manoeuvring, parking and collision avoidance, short-range radars should be capable to detect a wide range of objects all around the vehicle.

Initial sharing and compatibility studies for this type of radars are documented in ECC Report 334 [7]. There, it was concluded that in-band compatibility with EESS passive services is not possible. Therefore, in this Report, further refinements have been restricted to the other frequency ranges.

Radiodetermination applications in the 116-148.5 GHz band benefit from high range resolution and small form factors, making them very attractive for in-vehicle applications too. Being able to operate presence detection and gesture recognition systems in frequency bands separate from the 77-79 GHz automotive radar and 60 GHz communication bands will minimise the risk of interference.

With this in mind, this Report builds upon the work from ECC Report 334 and studies the candidate bands 116-130 GHz, 134-141 GHz and 141-148.5 GHz for both exterior (limited to bands adjacent to EESS (passive)) and in-cabin radars.

2 DESCRIPTION OF VEHICULAR RADIODETERMINATION APPLICATIONS AND TECHNOLOGY

2.1 EXTERIOR VEHICULAR RADAR APPLICATIONS

2.1.1 Application scenario

To perform different functionalities for driving assistance, cars are equipped with different types of radars that are integrated in specific positions onboard the vehicle as shown in Figure 1. Front and corner radars are currently used for applications requiring long and medium range such as automatic cruise control, lane keep, lane change assist, automatic emergency braking, etc.

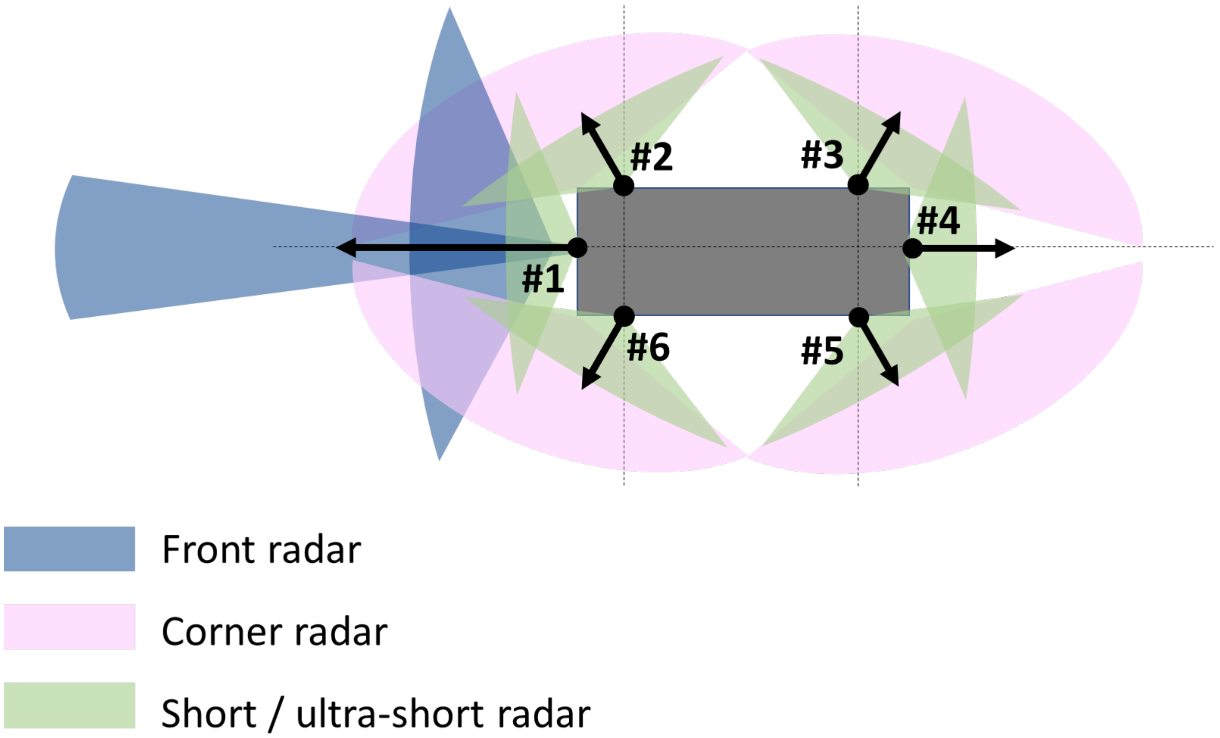


Figure 1: Considered exterior vehicular radar types

On the other hand, future applications providing the vehicle with higher degree of autonomy require short and ultra-short-range radars for front, side and rear-view (see green areas in Figure 1), such that 360° sensing is enabled. Those radars would allow to obtain a wide field of view (elevation and azimuth) in the close proximity of the vehicle and features like automated parking assistance or autonomous valet parking would be possible. To perform such features, the short-range detection radars should be capable to detect a wide range of objects different in nature to those traditionally detected for driving assistance radars (pedestrian, bicycles, vehicles, etc). Therefore, a wide range of target characteristics should be taken into account while assessing the technical parameters of the radars at this frequency range.

2.1.2 Frequency bands and incumbent systems

Taking into account initial studies documented in ECC Report 334 [7], the frequency ranges allocated to EESS (passive) are excluded from the investigations for exterior vehicular radars in this Report.

The following frequency ranges are therefore considered:

- 122.25-130 GHz;
- 134-141 GHz;
- 141-148.5 GHz.

Based on the applications identified in the European Common Allocation (ECA) Table [25], the sharing scenarios between exterior vehicular radars and existing services are described Table 1.

Table 1: Description of sharing studies

Interfered with service or application	Frequency band	Allocation Status
Earth Exploration Satellite Service (passive)	114.25-122.25 GHz (in-band) 148.5-151.5 GHz (adjacent band)	Primary Primary
Non-specific SRDs	122.25-123 GHz	
Radio Astronomy Service	123-130 GHz 130-134 GHz (adjacent band) 134-136 GHz 136-141 GHz 141-148.5 GHz	Secondary Primary Secondary Primary Primary
Fixed Service	130-134 GHz (adjacent band) 141-148.5 GHz	Primary Primary
Amateur Service	122.25-123 GHz 134-136 GHz 136-141 GHz	Secondary Primary Secondary
Amateur-Satellite Service	122.25-123 GHz 134-136 GHz 136-141 GHz	Secondary Primary Secondary

A graphical representation of the candidate frequency ranges and their relationship to the incumbent systems is included in Figure 2.

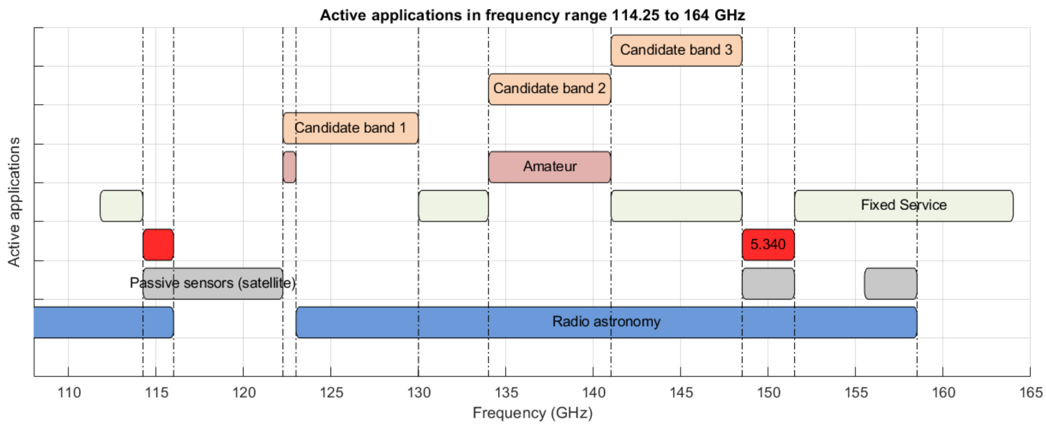


Figure 2: Frequency bands for exterior vehicular applications and incumbent systems

2.1.3 Technical parameters

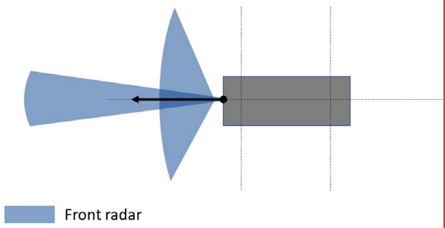
Radar products for automobile applications exist in the 24 GHz and 79 GHz frequency bands. No prototypes have been developed in frequency bands above 100 GHz; therefore, several hypotheses should be made to deduce radar characteristics at the bands considered in this Report.

Table 2 provides general assumptions applicable to different type of radars that could be designed in these bands. The specific set of parameters that have been used in the compatibility studies are listed in the following tables.

Table 2: General assumptions for automotive radars for exterior applications

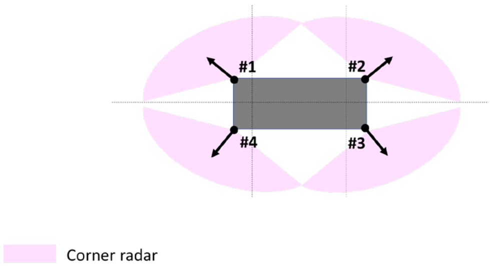
Parameter	Value	Comment
Frequency bands	122.25-130 GHz 134-141 GHz 141-148.5 GHz	
Bandwidth	1, 2, 4, 7, 14 GHz	Depending on the required range resolution of the application
Required SNR	15 dB	Typical value in lower frequency bands
RCS	−30 dBm² to +10 dBm² (Note 1)	For different type of objects related to short-range assist application
Radar loss	6 dB	Overall IF signal handling loss
Antenna height	0.4-1 m above road	
Typical duty cycle	25-50 %	
Note 1: Analysis of RCS values should be further developed to ensure that small objects such as sidewalk edges, bushes and others are represented in the analysis		

Table 3: Typical parameters for automotive front radars

Parameter	Value	Comment
Frequency bands	122.25-130 GHz 134-141 GHz 141-148.5 GHz	
Bandwidth	1 GHz	Front radars aim for long detection range and large range resolution.
Antenna height	0.7 m above road	0.7 is the midpoint between 0.4 and 1.0 meter
Number of such radars per vehicle	1	Only 1 front radar
Location and direction of such radars mounted on the vehicle		Located in the front of the vehicle, centred Directed towards front, zero degree elevation is assumed.
Antenna pattern	Radar A (Recommendation ITU-R M.2057-1 for 76-81 GHz [2])	See section 2.1.3.1 for details
Duty cycle (for each radar)	50 %	See ANNEX 2 for details of the definition of duty cycle in this context
Maximum radiated peak power (e.i.r.p)	+40 dBm	Radiated peak power during transmitter on time as defined in ETSI EN 303 883-1, section 5.3.3 [33].

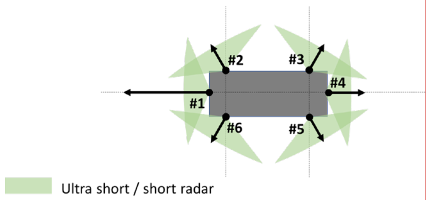
Parameter	Value	Comment
		Typically measured with a peak detector with 50 MHz BW, and integrated over the signal BW. e.i.r.p. may be adapted depending on the dynamics of the vehicle.
Maximum radiated mean power (e.i.r.p)	+35 dBm	Radiated mean power during transmitter on time as defined in ETSI EN 303 883-1, section 5.3.1 [33]. Typically measured with an average/RMS detector with 1 MHz BW, and integrated over the signal BW.

Table 4: Typical parameters for automotive corner radars

Parameter	Value	Comment
Frequency bands	122.25-130 GHz 134-141 GHz 141-148.5 GHz	
Bandwidth	4-7 GHz	Corner radars aim for short detection range and small range resolution
Antenna height	0.7 m above road	0.7 is the midpoint between 0.4 and 1.0 meter
Number of such radars per vehicle	4	It can be noted that at most 2 beams can overlap
Location and direction of such radars mounted on the vehicle		Located in the corner of the vehicle, 45° angle between main beam direction and front or back, zero degree elevation assumed
Antenna pattern	Radar C (Recommendation ITU-R M.2057-1 for 76-81 GHz [2])	See section 2.1.3.1 for details
Duty cycle (for each radar)	25 %	See ANNEX 2 for details of the definition of duty cycle in this context
Maximum radiated peak power (e.i.r.p)	+20 dBm	Radiated peak power during transmitter on time as defined in ETSI EN 303 883-1, section 5.3.3 [33]. Typically measured with a peak detector with 50 MHz BW, and integrated over the signal BW. e.i.r.p. may be adapted depending on the dynamics of the vehicle.

Parameter	Value	Comment
Maximum radiated mean power (e.i.r.p)	+15 dBm	Radiated mean power during transmitter on time as defined in ETSI EN 303 883-1, section 5.3.1 [33]. Typically measured with an average/RMS detector with 1 MHz BW, and integrated over the signal BW.

Table 5: Typical parameters for automotive short / ultra-short range radars

Parameter	Value	Comment
Frequency bands	122.25-130 GHz 134-141 GHz 141-148.5 GHz	
Bandwidth	4-7 GHz	Short radars aim for very short detection range and very small range resolution.
Antenna height	0.7 m above road	0.7 is the midpoint between 0.4 and 1.0 meter
Number of such radars per vehicle	6	It can be noted that at most 3 beams can overlap.
Location and direction of such radars mounted on the vehicle		60 degrees relative main beam offsets
Antenna pattern	Radar E (Recommendation ITU-R M.2057-1 76-81 GHz [2])	See section 2.1.3.1 for details
Duty cycle (for each radar)	25 %	See ANNEX 2: for details of the definition of duty cycle in this context
Maximum radiated peak power (e.i.r.p)	+20 dBm	Radiated peak power during transmitter on time as defined in ETSI EN 303 883-1, section 5.3.3 [33]. Typically measured with a peak detector with 50 MHz BW, and integrated over the signal BW. e.i.r.p. may be adapted depending on the dynamics of the vehicle.
Maximum radiated mean power (e.i.r.p)	+15 dBm	Radiated mean power during transmitter on time as defined in ETSI EN 303 883-1, section 5.3.1 [33]. Typically measured with an average/RMS detector with 1 MHz BW, and integrated over the signal BW.

2.1.3.1 Antenna radiation patterns

This section provides detailed definition of the antenna radiation patterns for front, corner and short / ultra-short range radars.

Recommendation ITU-R M.2057 [2] provides formulas for various radar types, although for the 76-81 GHz band. "Radar A" is a front radar, "Radar C" is a corner radar and "Radar E" is a short / ultra-short range radar. The following table provides information taken from Recommendation ITU-R M.2057.

Table 6: Extract (not all entries) from Recommendation ITU-R M.2057 "Table 1, Automotive radar characteristics in the frequency band 76-81 GHz"

Parameter	Units	Radar A Automotive radar for front applications for e.g. for ACC	Radar C Automotive high-resolution radar for corner applications	Radar E Automotive high-resolution radar, very short-range applications (e.g. parking-aid, CA at very low speed)
Sub-band used	GHz	76-77	77-81	77-81
Antenna height	m	0.3-1 above road	0.3-1 above road	0.3-1 above road
Antenna azimuth 10 dB beamwidth	degrees	Tx/Rx: ±10	Tx: ±23	Tx: ±50
Antenna azimuth 3 dB beamwidth	degrees	Tx/Rx: ±5	Tx: ±12.5	Tx: ±27
Antenna elevation -3 dB beamwidth	degrees	Tx/Rx: ±3	Tx/Rx: ± 5.5	Tx/Rx: ± 5.5

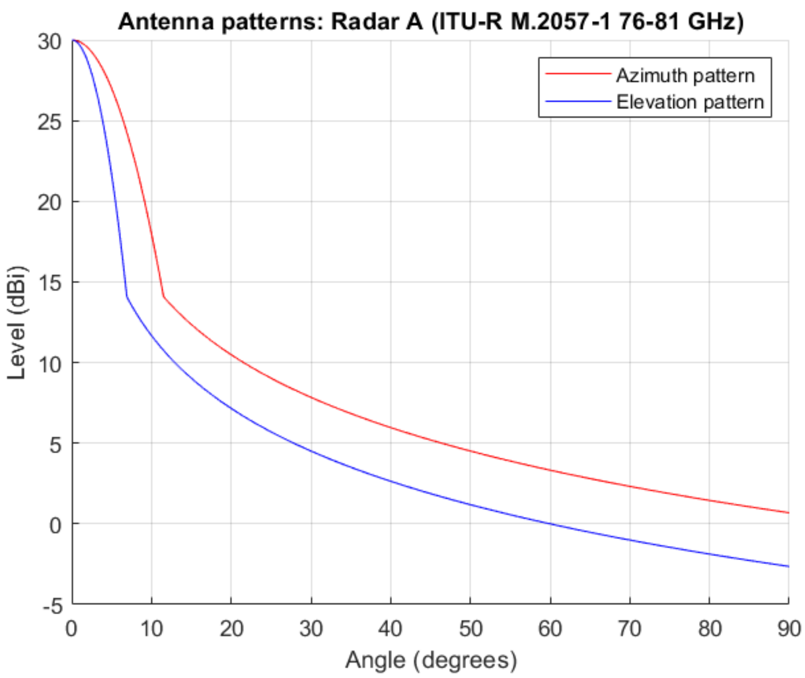


Figure 3: Antenna pattern for front radar applications (based on Radar A from Recommendation ITU-R M.2057 [2])

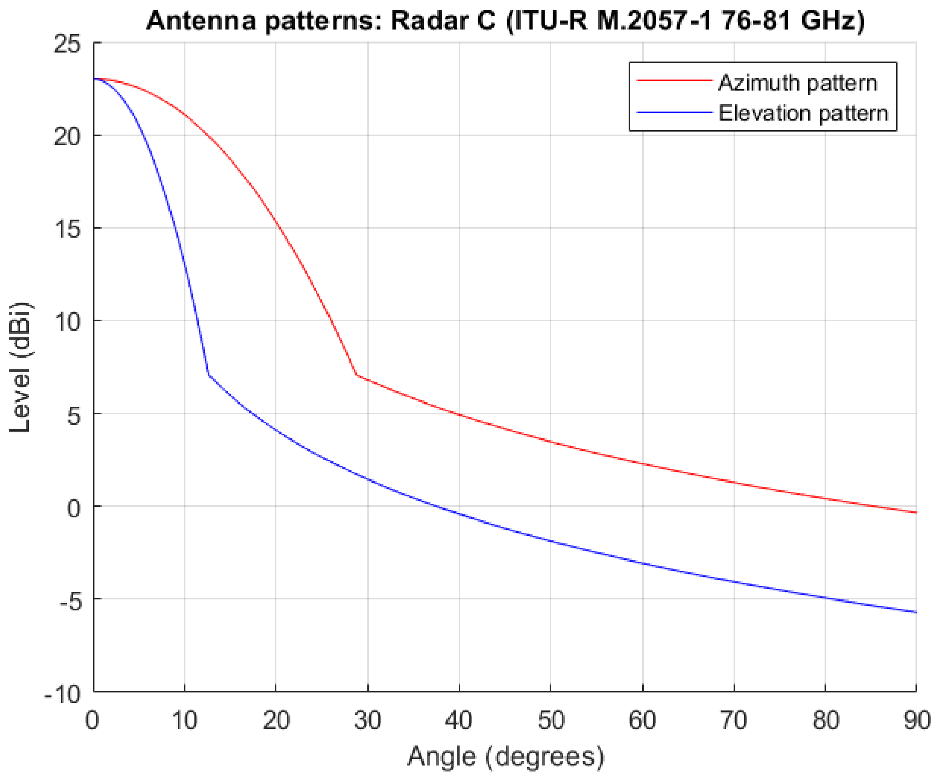


Figure 4: Antenna pattern for corner radar applications (based on Radar C from Recommendation ITU-R M.2057 [2])

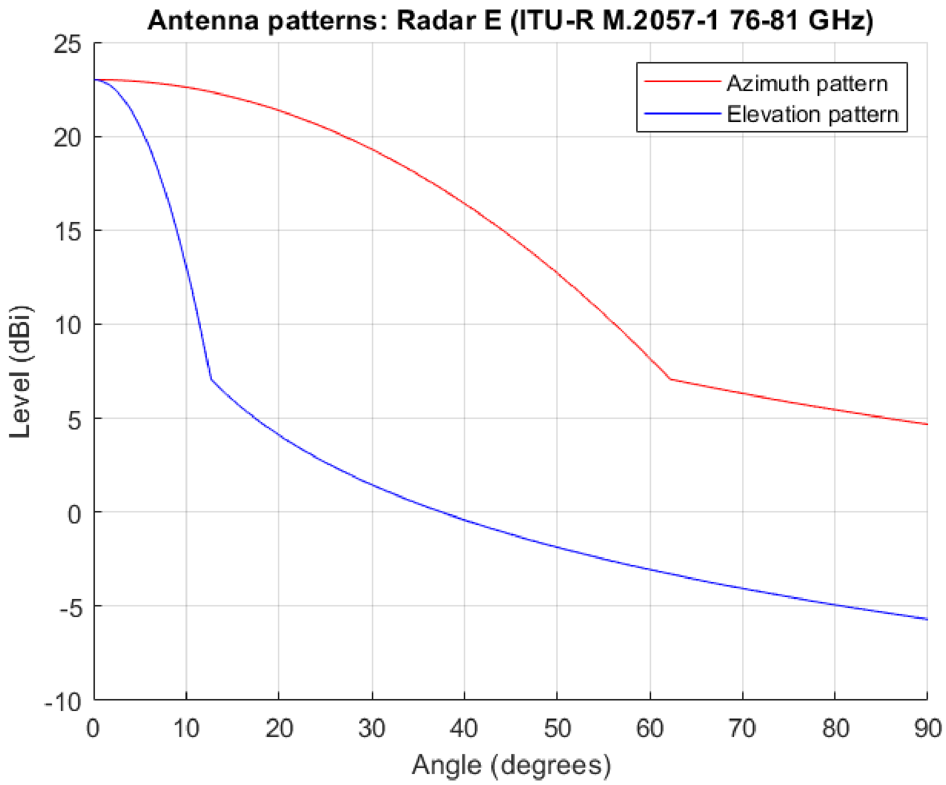


Figure 5: Antenna pattern for short/ultra-short radar applications (based on Radar E from Recommendation ITU-R M.2057 [2])

2.1.3.2 Out-of-band attenuation

For adjacent bands (e.g. EESS bands), the working assumption is that radars can ensure an absolute protection level of -50 dBm/MHz. This number might be further refined if less stringent values are proven to lead to positive margins for the compatibility studies. A positive margin indicates that the interference criterion is fulfilled and a negative margin that the criterion is violated.

Depending on the radar design and its mode of operation (transmit power, signal bandwidth, modulation technique) or antenna design (MIMO, beamforming) different OOBE patterns may arise, with different decay shapes past the operating frequency range (OFR). The working assumption is that such out-of-band emission (OOBE) patterns do not need to be specified, providing only the protection level towards adjacent (EESS) bands is needed.

Depending on its OOBE pattern, a given radar may either be able to use the whole candidate radar band if it can operate directly at the band edges (e.g. if the power level at the OFR edge is already lower than the protection level for adjacent bands), or it may be able to use only a fraction of the band (e.g. 80%) if it requires a 'guard range' margin (for instance 1 GHz) to reach the protection level for adjacent bands. The guard range is illustrated by Figure 6 for front radars and Figure 7 for corner and short/ultra-short range radars.

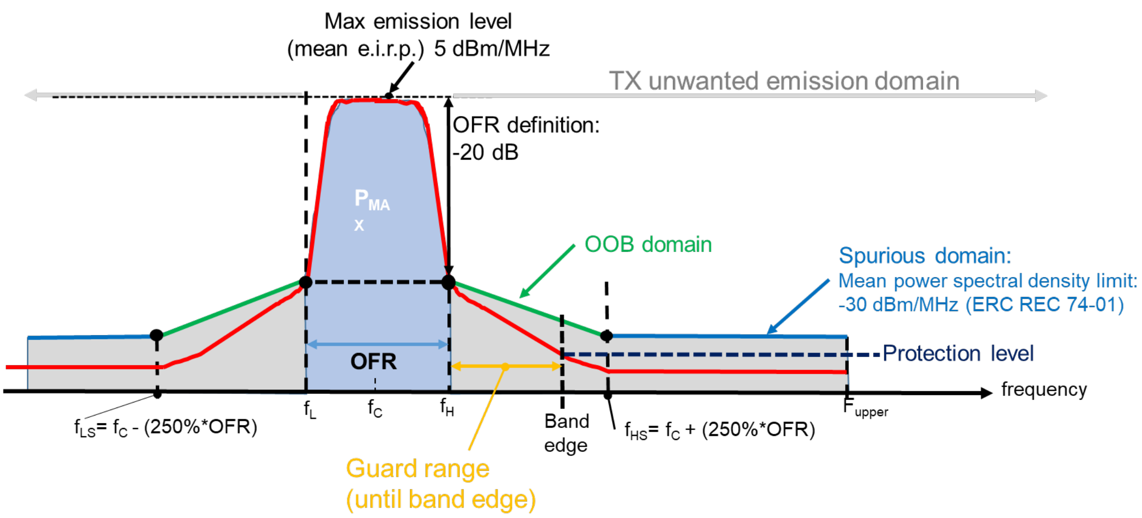


Figure 6: Illustration of Tx unwanted emissions level for front radar

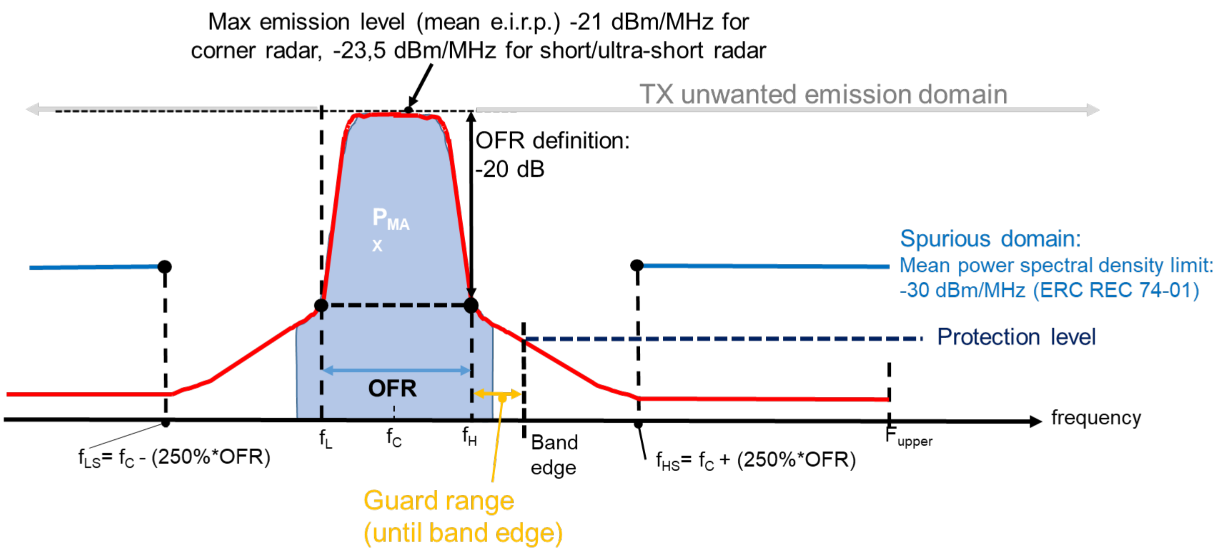


Figure 7: Illustration of Tx unwanted emissions level for corner and short/ultra-short range radars

2.1.4 Market size

Even though estimation of the market size is not provided in the ETSI TR 103 498 [1], it is expected that the number of vehicles equipped with this type of systems be smaller than those equipped with radars used for car safety and road safety. Indeed, the front radars or corner radars are often used by Advanced Driver-Assistance Systems (ADAS) to avoid collisions and accidents while driving; on the other hand, the short-range assist radars analysed in this section would be mainly deployed in vehicles with high level of autonomy.

2.2 IN-CABIN VEHICULAR RADAR APPLICATIONS

2.2.1 Application scenario

Similar to the other categories of millimetre-wave radars, the frequency range 116-260 GHz enables emerging applications with high range resolution and low form factors. This is important especially for in-cabin use where both aesthetics and size considerations matter. Common characteristics of these use cases (particularly in-cabin applications) depend on the inherent small form factors enabled by high frequencies and short wavelengths, respectively. Another advantage of the frequency range 116-260 GHz for interior monitoring is high velocity sensitivity and resolution due to the high Doppler frequency shift associated with the target motion. High velocity sensitivity allows better detection of tiny motions such as breathing baby, heart vibration and slow gestures. Given the inherent need for detecting motion and presence of individual persons, limbs or fingers, digital beam forming and MIMO technology with a high angular resolution is necessary.

For all these applications, the privacy-preserving nature of the radar sensing is a fundamental property, and such sensors are used to assess the situation in a volumetric space. The situation is assessed by detecting the overall presence of a human or parts of a human body, e.g. micro-motion caused by heartbeat, breathing, or assessing the physical characteristics (the contour) of the objects. Some functions may also encompass the detection of non-human presence, like animals or non-living objects.

In-cabin applications include contactless gesture control, presence detection (including baby/child detection) and vital sign monitoring such as respiration rate, heart rate and heart rate variation. The use of higher frequency ranges further reduces the risk of interference with other automotive radars (e.g. 77 GHz or 79 GHz radars) or wireless communication devices using the 60 GHz band. With the increasing miniaturisation, angular resolution offers the possibility to discriminate between multiple seats inside a car with a single radar sensor with beamforming or MIMO capability.

Overview of planned common use cases:

- Gesture detection/proximity detection: for example, a fine finger motion for manipulating controls/settings;
- Passenger presence and seating location detection: for example, assessing occupancy at one or more seats, which can be in a vehicle or in a room. Such functions are often meant to classify the occupancy, e.g. distinguishing between a bag and a person on a seat, thus requiring accurate scene information. Distinguishing between multiple occupants can be done with digital beam forming;
- Forgotten occupant detection: for example, the presence of vital signs is detected by evaluating micro-motion caused by a heartbeat and/or breathing. This use-case includes also child presence detection, a human safety related feature, which is going to be awarded by the European New Car Assessment Programme (Euro NCAP) from 2023. The main function is to detect babies and small children left behind in a vehicle and to prevent harm or the possible death from heat stroke;
- Occupant posture detection: for example, assessing the contour of the body to determine upper body location, e.g. in support of vehicle safety systems deployment;
- Upper body/head position and tracking: for example, for detection of driver attentiveness of occupant’s vital sign tracking (heartbeat/breathing): for example, assessment of the physical well-being – e.g. inside a vehicle– of a person (or persons) in the scene. The presence and evolution of life signs is detected by assessing micro-motion caused by a heartbeat and/or breathing;
- Intrusion detection system.

Figure 8 provides examples of sensor positions inside a passenger car.

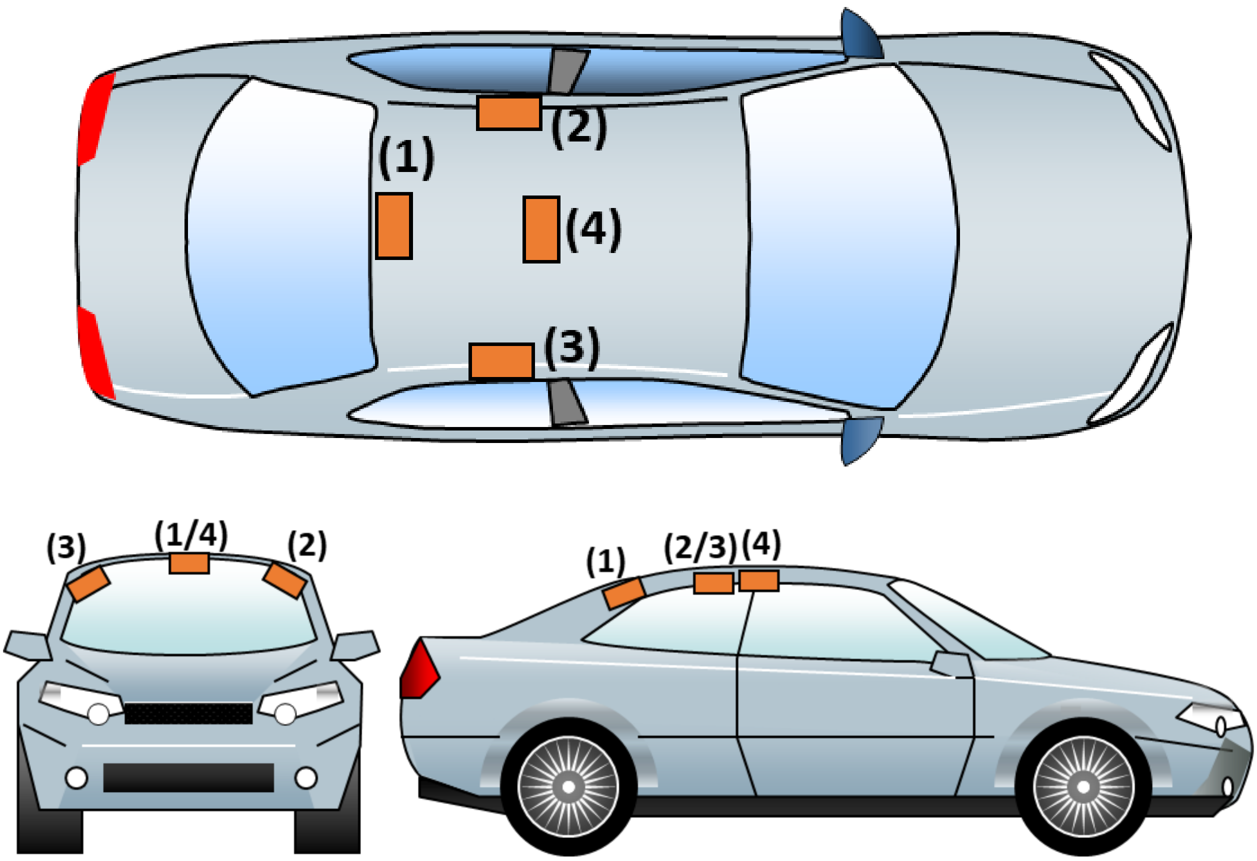


Figure 8: Examples of possible mounting positions for radar sensors

Examples of suitable mounting positions are above the second seat row (see position 1 in Figure 8) or in the centre of the ceiling (see position 4 in Figure 8) or next to the roof grab handle (see position 2 and 3 in Figure 8). Depending on the functional requirements of the desired application, the module can be also located at a position not shown in the figure. The sensor is expected to meet all the technical requirements from Table 7 at the selected position.

The typical position of the in-cabin radar sensor is above second seat row or middle of the car's roof. The sensor is positioned so as to illuminate the inside of the car's cabin. Depending on the application the focus can be on the second and third row or on the whole of the car's cabin. It is intended to integrate the in-cabin radar sensors inside cars with metallic roof (mounting position 1, 2, 3, and 4) and inside cars with sunroof (mounting position 1, 2, and 3). It is not intended to integrate in-cabin radar sensors inside convertible cars. The construction of the convertible car roof is not proving optimal mounting positions for in-cabin radar to fulfil application requirements.

The in-cabin operation is shielded by the car body, typically mounted on the car ceiling to get a large, unobstructed view to the surveillance area. The longest distance in the observed volume is less than 3 m.

2.2.2 Frequency ranges and incumbent services

Building upon the results from ECC Report 334, the following frequency ranges are considered in the compatibility studies for in-cabin vehicular radars:

- 116 GHz to 130 GHz;
- 134 GHz to 141 GHz;
- 141 GHz to 148.5 GHz.

The incumbent services are identical to those listed in Table 1 for exterior vehicular applications.

The possible interference scenarios are divided into to two categories:

- Interference over terrestrial line-of-sight paths;
- Interference to space borne passive satellite receivers over line-of-sight paths.

2.2.2.1 Interference over terrestrial paths

Related services are:
- Fixed Service (FS) links (PP and BWA);
- Terrestrial Radio Astronomy Service (RAS);
- Amateur Service receivers.

2.2.2.2 Interference to space borne passive satellite receivers over line-of-sight paths

Satellite systems to be considered:
- MWI, elevation angle at the ground 36.7°;
- EUMETSAT, elevation angle at the ground 37°;
- System N1 (Nadir), elevation at ground 90°, and (outer), elevation at ground 33.1°.

2.2.3 Technical parameters

Table 7 gives an overview of the technical parameters of in-cabin vehicular radar applications used for compatibility studies.

Table 7: Technical parameters of in-cabin vehicular radar

Parameter	Value	Notes
Modulation scheme	Examples of currently considered modulation schemes: ▪ Frequency Modulated Continuous Wave (FMCW) ▪ Pulsed ▪ OFDM	The provided list should not be considered in any case as complete or limiting further development in modulation schemes.
Operating frequency range (OFR)	116 GHz to 130 GHz 134 GHz to 141 GHz 141 GHz to 148.5 GHz	
Mean e.i.r.p. spectral density	-30 dBm/MHz	Limit for mean e.i.r.p. spectral density. Defined as in ETSI EN 303 883-1 [33]
Mean e.i.r.p.	3 dBm	Limit for mean e.i.r.p. over whole bandwidth Defined as in ETSI EN 303 883-1
Peak e.i.r.p.	16 dBm	Limit for peak e.i.r.p. over whole bandwidth Defined as in ETSI EN 303 883-1
Minimum bandwidth	1 GHz	
Available modulation bandwidth	14.5 GHz	Maximum possible bandwidth
Polarisation loss	3 dB	

Table 8: Representative values for parameters of in-cabin vehicular radar

Parameter	Value	Notes
Sweep-time	10 µs to 15 ms	For a single frequency sweep over entire modulation bandwidth
Duty cycle	5-50 %	Duty cycle as ratio of transmission time to singe cycle time
Cycle time	5 ms to 250 ms	
Bandwidth	2 GHz to 14 GHz	
Peak carrier power	0 dBm to 6 dBm	
Mean power	+3 dBm	

2.2.3.1 Antenna gain

The in-cabin vehicular radar application monitors the inside of vehicle cabins and the close vicinity of the car. For this purpose, a representative antenna would have a wide field of view in both azimuth and in elevation direction to illuminate the cabin of the vehicle. It is also possible to design in-cabin sensors that can illuminate specified areas of the cabin separately, using for example beam forming techniques. The antenna gain for in-cabin vehicular radar is therefore mainly use-case dependent. The maximum range for in-cabin applications is usually just a few meters.

Figure 9 shows an example of a simulated in-cabin antenna pattern. The antenna gain of this antenna is 10 dBi.

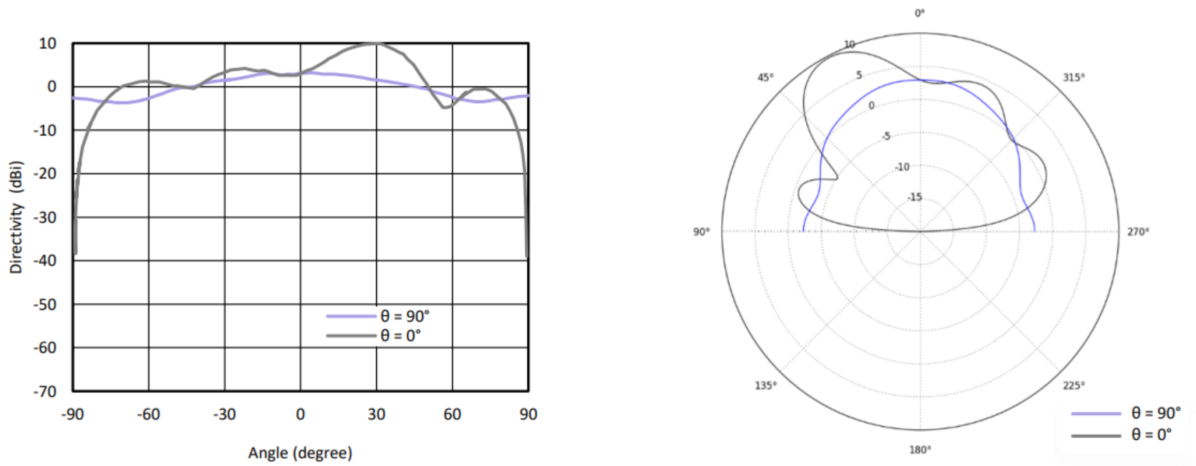


Figure 9: Simulated antenna pattern of a representative in-cabin sensor

2.2.3.2 Car attenuation measurements at 122.5 GHz

Dedicated measurements have been performed to evaluate the attenuation provided by car bodies, both from vehicles with a conventional roof and with a sunroof. These measurements are summarised in ANNEX 1.

Based on the measurements, the car attenuation values from Table 9 are used for the sharing and compatibility studies. These correspond to the minimum value of the minima of all measurements (single entry study) and the mean value of the minima of all measurements (aggregated study) respectively.

Table 9: Attenuation values used in sharing and compatibility studies

Case \ Angle	90°	35°	0°
Single entry study	27 dB	15 dB	18 dB
Aggregated study	33 dB	27 dB	25 dB

2.2.4 Market size

Table 10 shows the estimated market size for in-cabin vehicle radar devices throughout Europe sub-divided for all frequency bands 57-64 GHz, 116−130 GHz, 134−148.5 GHz, in which the systems are assumed to be operated, depending on the results of the compatibility and sharing studies.

The Report ITU-R SM.2057 [2] described the expected density of cars for highways and urban/suburban scenarios peak hours during the weekdays, 123 and 330 vehicles/km², respectively.

This Report only considers the urban/suburban scenario.

Table 10: Estimated device densities of vehicle interior radar devices

Parameter	Value
Fraction of devices sold in the band 57 GHz to 64 GHz	33 %
Fraction of devices sold in the band 116 GHz to 130 GHz	33 %
Fraction of devices sold in the band 134 GHz to 148.5 GHz	33 %
Estimated peak hours vehicle density in cars/km²	330

3 SHARING AND COMPATIBILITY STUDIES WITH RADIO ASTRONOMY SERVICE

3.1 RADIO ASTRONOMY SERVICE SPECIFICATIONS

Radio astronomy systems make observations across the whole of the accessible electromagnetic spectrum, which extends well beyond the "visual" or “optical” region. Every frequency range provides its own insights and usually requires its own variety of telescopes and detectors. Radio astronomers study objects that radiate or absorb energy at frequencies within the radio spectrum: when ground-based, studies are conducted wherever the atmosphere is at all transparent in the range from 13 MHz to 2 THz (Handbook on Radio Astronomy [8]).

Millimetre radio astronomy spans over the range 72-275 GHz (sub-mm above these frequencies). This range gives unique insights into many aspects of the Universe. Unlike at lower frequencies, the main continuum emission mechanism in the mm range is through thermal emission (emission from a black body), allowing sampling of the distribution and physical properties of dust in various environments. Many molecules, free radicals or ions have their rotation lines within this range (as partly reflected in Recommendation ITU-R RA.314-10 [9]). As of February 2019, around 200 molecules (with up to 12 atoms) have been detected in the interstellar medium and circumstellar shells [10]. The majority of these detections have been made by millimetre radio telescopes; half of these detections were made by the IRAM 30 m antenna alone.

The high frequency of observation permits a better angular resolution for a given instrument size. This is one of the main reasons behind the Event Horizon Telescope, a world-wide astronomical collaboration that made the first image of a black hole in 2019 (a supermassive black hole lying at the centre of the M87 galaxy).

Last in this non-exhaustive list, the mm domain is a way to sample the Universe in its infancy since the redshift of the infrared peak of galaxies compensates (or more) for the dimming due to distance. Hence the most distant (and youngest) objects in the Universe are detected in the mm-range.

Currently, Europe hosts the world's most sensitive millimetre single antenna and the most sensitive millimetre interferometer in the Northern Hemisphere, the IRAM 30 m in Spain and NOEMA in France respectively. The site characteristics are provided in Table 11.

Both the 30 m IRAM and NOEMA observe more than 50% of the time in the bands 120-175 GHz and 200 - 275 GHz. As the quest for new molecules (including the search for amino acids) goes on, one needs ever more sensitive instruments and observations. Recognising also that the astrophysical lines appear at certain frequencies imposed by physics (often not known prior to the observations), and that a confirmed detection of a new species requires the detection of at least a few lines of that species (spread over the whole band), the RAS has allocations (primary or secondary) and footnotes in the Radio Regulations (RR No. 5.149 or RR 5.340) to protect these allocations [26] in most parts of the range.

The most sensitive measurement mode is continuum observations, which are also used extensively at both European observatories mentioned above. Therefore, in this Report only calculations for the continuum mode are presented.

Table 11: European radio astronomy observatories operating in the frequency range 116-148.5 GHz

Observatory Name	Administration	Longitude (E), Latitude (N)	Elevation (m AMSL)	Observing mode	Geographical characteristics
NOEMA	France	05°54'28" 44°38'02"	2560	single dish, interferometry, VLBI	Isolated high mountain top in the Alps (Plateau de Bure)
IRAM 30 m	Spain	-03°23'34" 37°03'58"	2850	Single dish, VLBI	Sierra Nevada Mountain (Pico Veleta)

The sharing studies with respect to the RAS, which are presented in the following section, are carried out as single-interferer worst-case calculations. For this aim, the effective (time-averaged) e.i.r.p. value of the transmitters is inferred. In the second step, the received power at the RAS station is compared with the threshold levels, which specify the maximum interference power not to be exceeded.

3.2 RAS PROTECTION THRESHOLDS

The threshold levels of interference detrimental to Radio astronomy continuum observations (CO), spectral-line observations (SLO) and very long baseline interferometry (VLBI) can be found in Recommendation ITU-R RA.769-2 [11] for centre frequencies from 13.385 MHz up to 270 GHz. Table 12 shows the protection criteria for CO near the relevant frequency ranges for this study.

Table 12: Radio astronomy protection criteria for continuum observations

Centre frequency (GHz)	Assumed bandwidth Δf (MHz)	Threshold Interference input power ΔPH (dBW)	Reference
89	8000	-189	Recommendation ITU-R RA.769-2, table 1 [11]
150	8000	-189	
224	8000	-188	
270	8000	-187	

For the RAS compatibility studies in this Report continuum observations are assumed, as this is the most sensitive observing mode. The frequency range of interest (116 to 148.5 GHz) is not well sampled by the Recommendation ITU-R RA.769-2, table 1 [11] entries, but the Recommendation gives guidance on how to calculate the threshold values, which primarily depend on the atmospheric and receiver contributions to the antenna system temperature.

Following the guidance given in Recommendation ITU-R RA.769-2, and in accordance with the latest information from experts in low-noise receiver developments, the receiver noise temperature can be modelled according to the following formula:

$$T_R = \max\left(30K, \frac{4hf}{k_B}\right) \quad (1)$$

Where:

- h and k_B are the Planck and Boltzman constants;
- f the frequency under consideration.

Figure 10 shows the evolution of T_R with frequency.

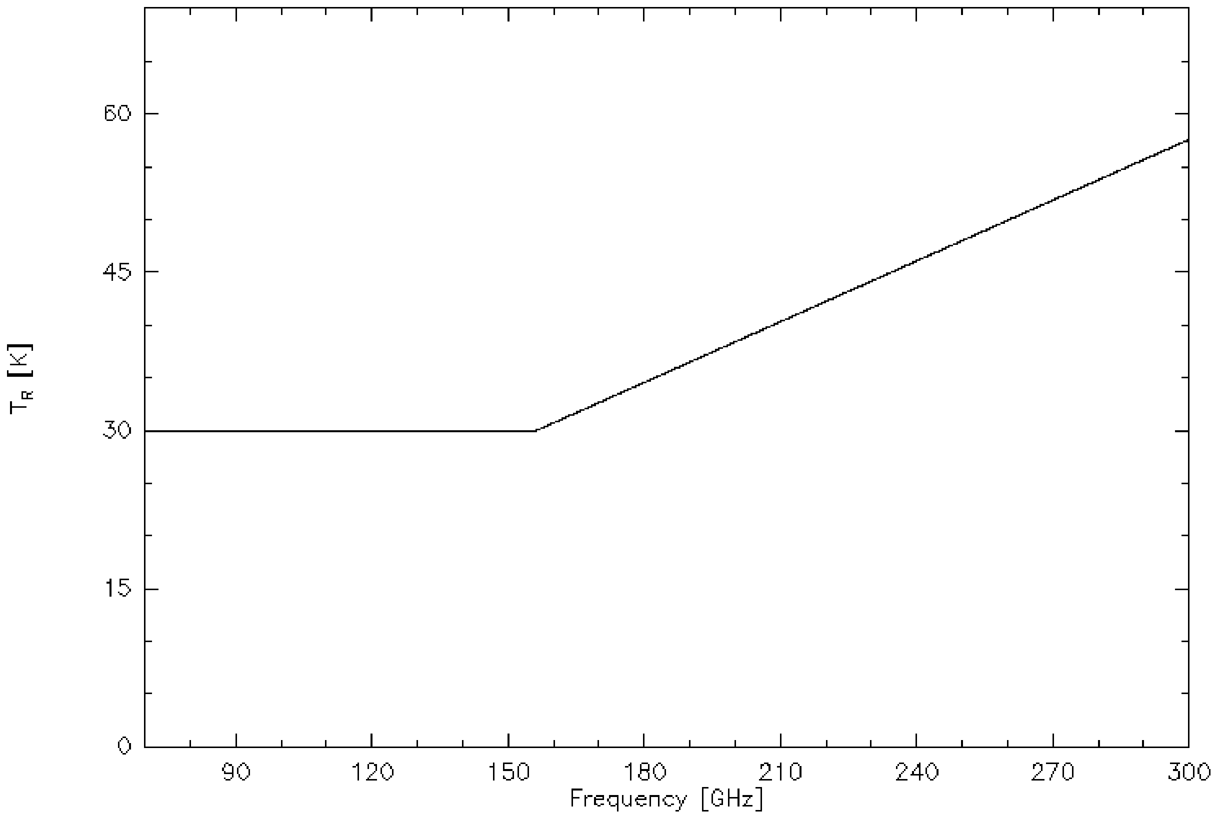


Figure 10: Receiver noise temperature T_R as a function of frequency

Following the guidance given in Recommendation ITU-R RA.769-2 [11], the minimum atmospheric noise temperatures (T_A) were computed for the Atacama Large Millimeter/submillimeter Array (ALMA) [12] site. Our computations reproduce those indicated in the in Recommendation ITU-R RA.769-2, table 1 and table 2 at the specified frequencies. The spectral line channel bandwidth applicable in the 70 GHz to 300 GHz range is 1 MHz. However, the frequency spacing used in Figure 11 and Figure 12 is 40 MHz for practical reasons. The calculation can be done on a finer grid if needed.

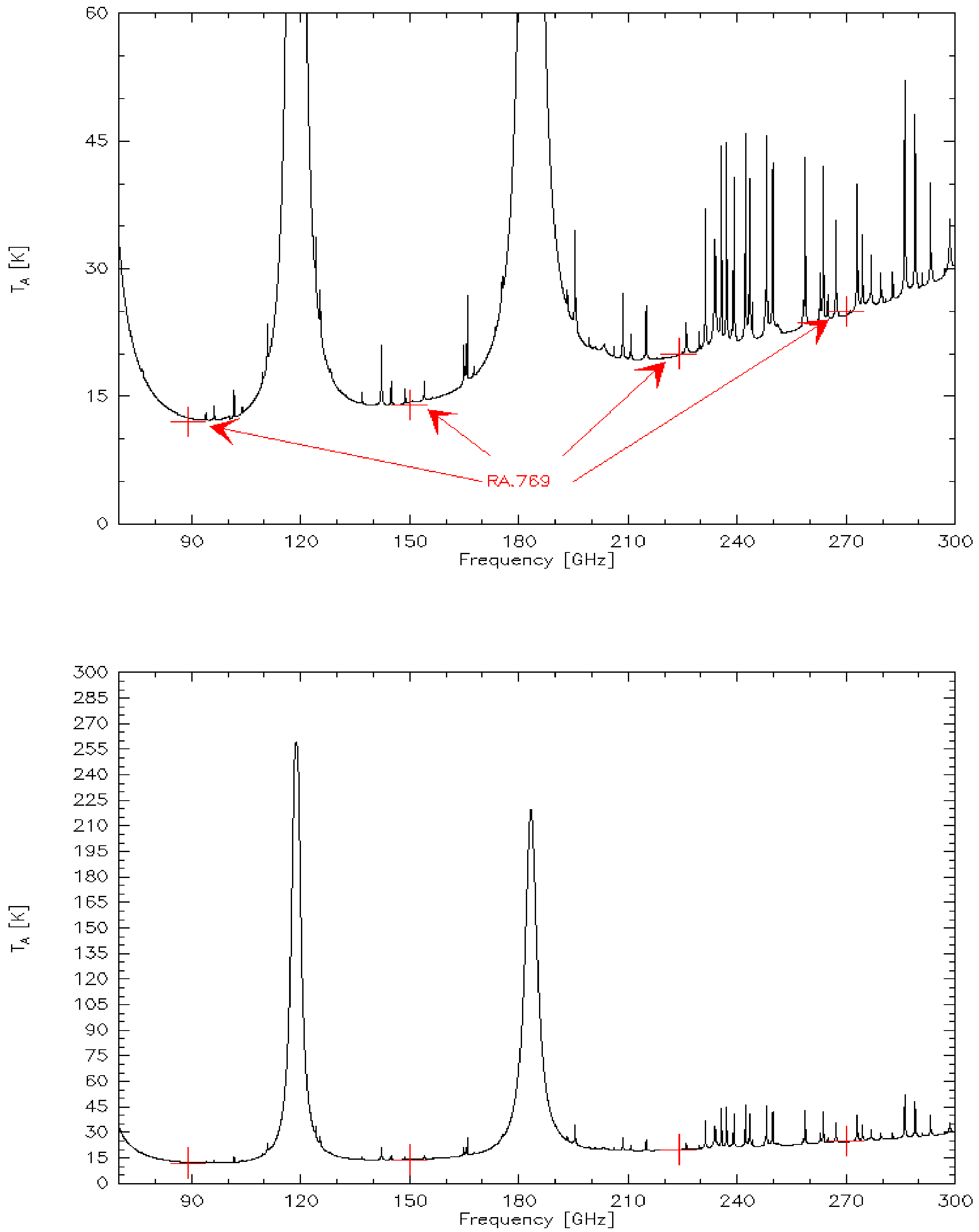


Figure 11: Minimum atmospheric noise temperature T_A as a function of frequency. Values contained in Recommendation ITU-R RA.769-2 are indicated by the red crosses (at 89, 150, 224 and 270 GHz) – Figure above provides a zoomed sight

Figure 11 shows the evolution of T_A with frequency. The prominent atmospheric lines of O_2 (below 70 GHz and at 116 GHz), H_2O (at 183 GHz) and the many fainter and narrower O_3 lines are clearly visible. The numbers in Recommendation ITU-R RA.769-2 were computed assuming certain RAS receiver bandwidths. Above 100 GHz, a bandwidth of 8 GHz is typically applied to calculate the entries for continuum observations. Therefore, the effective atmospheric temperature as displayed in Figure 11 needs to be smoothed with a box-car filter of width 8 GHz before using the numbers for the power threshold calculation. The result of the box-car filtering is presented in Figure 12.

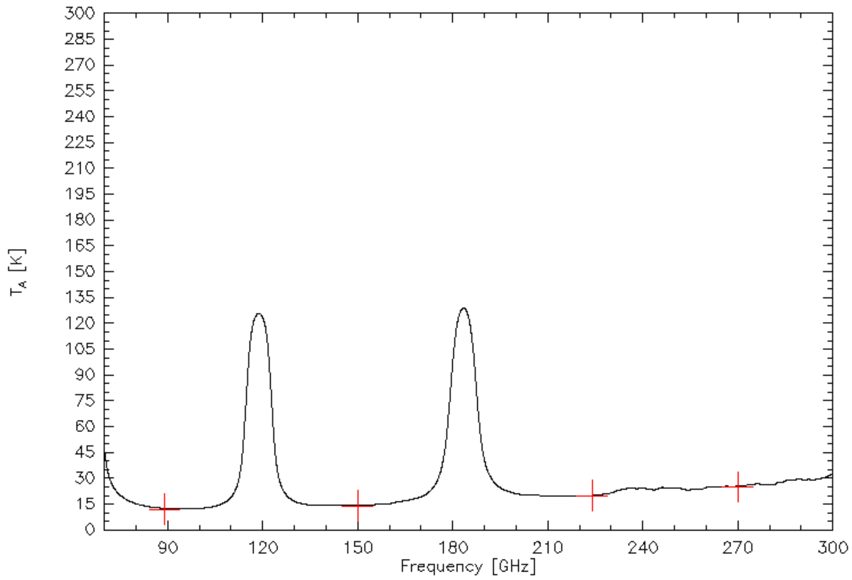


Figure 12: Minimum atmospheric noise temperature T_A after smoothing with a box-car filter (kernel width: 8 GHz)

With the atmospheric and receiver contributions to the antenna temperature, RAS power threshold limits can be calculated for any frequency, assuming a RAS bandwidth of 8 GHz. For the subsequent studies in this Report, the bands and resulting power threshold levels presented in Table 13 are used. It has to be noted that for the RAS compatibility study in this Report a different atmospheric propagation algorithm was used (namely the one proposed in Recommendation ITU-R P.676-12 [5]), which produces slightly different results compared to the (more site-specific) atmospheric model used at the Atacama Large Millimeter/submillimeter Array (ALMA) [12], which formed the basis for the table entries in Recommendation ITU-R RA.769-2 [11]. The least deviation is obtained when the "high latitude summer" profile (see Recommendation ITU-R P.835-6 [6]) is used.

Table 13: RAS frequency bands and power threshold levels used in this Report

Centre frequency (GHz)	T_R (K)	T_A (K)	Threshold level dBW
120	30.0	111.8	-184.1
130	30.0	12.5	-189.3
140	30.0	10.7	-189.5

3.3 EXTERIOR VEHICULAR RADARS

3.3.1 Calculation of the effective power of "Exterior vehicular radars"

The following frequency bands are relevant for considering the potential for sharing (co-channel) between radio astronomy service and radiodetermination devices intended to be mounted on vehicles as described in section 2.1.2:

- 123-130 GHz;
- 130-141 GHz;
- 141-148.5 GHz.

The calculation of the effective (time-averaged) e.i.r.p. value is summarised in Table 14. The various entries and factors are explained in the following sections. As the atmospheric attenuation at these frequencies is strongly frequency-dependent (owing to spectral lines of oxygen and water vapour in the atmosphere), three example RAS bands centred around 120, 130 and 140 GHz are considered. The 120 GHz frequency is heavily impacted by spectral lines of oxygen in the atmosphere, which leads to significantly smaller coordination distances.

Table 14: Calculation of effective e.i.r.p. values of various car radar transmitters

	Front radar	Corner radar	Short/ultra-short radars
RAS frequency	A: 120 GHz B: 130 GHz C: 140 GHz		
RAS bandwidth	8 GHz		
RAS threshold (Recommendation ITU-R RA.769-2 [11])	A: –154 dBm B: –159 dBm C: –159 dBm		
Number of radars mounted on the vehicle	1	4	6
Radiated mean pulse power (e.i.r.p.)	35 dBm	15 dBm	15 dBm
Radar signal bandwidth	1 GHz	4 GHz	7 GHz
Bandwidth correction factor (details in 3.3.2)	0 dB	0 dB	0 dB
Duty cycle (details in 3.3.3)	50% (–3 dB)	25% (–6 dB)	25% (–6 dB)
Radar antenna off-pointing gain (details in 3.3.4)	0 dB	0 dB	0 dB
Effective radiated power into RAS band (e.i.r.p., time-averaged)	32 dBm	9 dBm	9 dBm
Clutter loss (single-interferer worst-case) (details in 3.3.5)	0 dB	0 dB	0 dB
RAS antenna gain	0 dBi	0 dBi	0 dBi
MCL	A: 186 dB B: 191 dB C: 191 dB	A: 163 dB B: 168 dB C: 168 dB	A: 163 dB B: 168 dB C: 168 dB

3.3.2 Bandwidth correction factor

Given that the bandwidth values considered for this application range between 1 GHz and 7 GHz, and that the RAS power threshold is provided for a reference bandwidth of 8 GHz, there is no need to apply a bandwidth correction for the calculation of the effective power falling into the RAS frequency band.

3.3.3 Duty cycle

The typical duty cycle values from Table 14 range from 25% to 50% for the considered type of radars. As the RAS thresholds are calculated over an integration time of 2000 s, the radar Max.mean power has to be converted to a time-average value for the further calculations, based on the duty cycle.

3.3.4 Radar antenna pointing

The antenna pointing directions are not considered here, as in the framework of a single-interferer worst-case study, the underlying assumption is that there could be a single car somewhere in the vicinity, which is orientated such that one of its radar systems is directed to the RAS station both in terms of azimuth and elevation, and thus the full forward gain of its antenna applies meaning 0 dB of antenna off-pointing gain.

3.3.5 Clutter loss

The available ITU-R Recommendations related to the clutter loss do not cover frequencies in the range 116 to 150 GHz. For example, the Recommendation ITU-R.P.2108-0 [3] for the prediction of clutter loss is limited to 100 GHz. During the preparation of ECC Report 334, which is very similar to this Report, guidance was sought from the ITU Working Party 3M in charge of the propagation issues concerning the quantification and application of the clutter loss, including the effect of obstacles in the signal path, such as guardrails. WP 3M noted the difficulty to extend the Recommendation ITU-R P.2108-0 for frequencies above 67 GHz for terrestrial paths and above 100 GHz for slant paths because of the lack of measured data on which these models were based. WP 3M advised that in the single entry interferer scenario and for unobstructed signal paths (unobstructed by clutter between roads or highways and the radio telescope), free space loss plus atmospheric attenuation using slant paths as defined in Rec ITU-R P.676-12 [5] apply. WP 3M also considered that the clutter due to guard rails cannot be considered as a constant factor. For the aggregated scenario, only interferers in line of sight (LOS) have to be considered. Non-line of sight (NLOS) interferers could be neglected.

Therefore, no clutter loss was considered in the sharing and compatibility study for the single entry interferer scenario used in section 3.5.2.

3.4 IN-CABIN VEHICULAR RADAR

3.4.1 Calculation of the effective power of in-cabin vehicular radar

Table 15 summarises the parameters used for the interference study with in-cabin vehicular radar. As the atmospheric attenuation is strongly frequency dependent, three examples of RAS bands centred around 120, 130, 140 GHz with 8 GHz bandwidth are considered.

Table 15: RAS system parameters for in-cabin studies

Parameter	Value
RAS frequency	A: 120 GHz
	B: 130 GHz
	C: 140 GHz
RAS bandwidth	8 GHz

Parameter	Value
RAS thresholds (Recommendation ITU-R RA.769-2)	A: -154 dBm B: -159.3 dBm C: -159.3 dBm
Peak e.i.r.p.	6 dBm
Mean e.i.r.p.	3 dBm
Radar bandwidth	8 GHz
Duty cycle	50% (-3 dB)
In-cabin exit loss	15 dB
Effective radiated power into RAS band	-12 dBm
Clutter loss	0 dB
RAS antenna gain	0 dBi
MCL	A: 142 dB B: 147.3 dB C: 147.3 dB

3.4.2 Bandwidth correction factor

In the calculations, the bandwidth of 8 GHz was considered for in-cabin radar. This is the worst-case scenario, where the radar has the same bandwidth as the reference bandwidth of RAS. Therefore, in this case, there is no need to consider bandwidth correction factor in calculations of the effective power.

3.4.3 Duty cycle

In the calculations, 50% duty cycle is considered for in-cabin radar. Representative duty cycle for in-cabin radar is in the range of 5% to 50% (see Table 8). The duty cycle for in-cabin radar is usually defined as the transmission time to cycle time of radar device. Here it is assumed that the in-cabin radar is active over 2000 s of the integration time with a duty cycle of 50%. The mean e.i.r.p., over 2000 s with 50% duty cycle, is 3 dBm.

3.4.4 Clutter loss

No clutter loss was considered in the sharing and compatibility studies for single entry scenarios.

3.4.5 In-cabin exit loss

Exit loss for in-cabin vehicle radar sensor was determined through measurements (see section 2.2.3.2 and ANNEX 1). The in-cabin exit loss for single sensor study for the three measured incidence angles is collected in Table 16. The position and orientation of a vehicle with active in-cabin radar towards the RAS station changes as the vehicle is driving on the road. The angle that is to be considered for in-cabin exit loss will also change with the varying position, orientation and height difference of the vehicle toward the RAS station. Therefore, it is proposed to use the smallest in-cabin exit loss measured at 35° of 15 dB as worst-case scenario (see Table 16). To notice is that this corresponds to a worst case for vehicle orientation (RAS station on side of vehicle) and a vehicle standing still with opened sunroof and windows.

Table 16: In-cabin exit loss for single sensor case as a function of the incident angle

90°	35°	0°
27 dB	15 dB	18 dB

3.5 SINGLE ENTRY INTERFERENCE STUDIES

The results reported in this Report are based on single entry interference studies. Interference studies considering an aggregate scenario have not been performed for short-range assist devices. It is expected that single entry interference studies provide a reasonable approximation of an aggregate scenario.

3.5.1 Path attenuation maps for line of sight regions around telescopes NOEMA and IRAM

To calculate the path propagation losses, compatibility studies involving radio astronomy often use the model provided in Recommendation ITU-R P.452-16 [4]. For this study however, the frequencies are outside of the range of this propagation recommendation. Using P.452-16 with the highest possible frequency of 50 GHz reveals that there is a very sharp gap in the derived attenuation between line-of-sight (LOS) and trans-horizon paths. Therefore, this study proposes to restrict the analysis to line-of-sight (LOS) cases and assumes that the propagation loss is determined by pure LOS attenuation plus atmospheric dampening. LOS loss depends on distance and frequency as follows:

$$L[dB] = 92.4\ dB + 20 \cdot log(d[km]) + 20 \cdot log(f[GHz]) \tag{2}$$

while the atmospheric loss is a function of the physical parameters of the atmosphere leading to a height-dependent refractive index which bends the ray of light. Recommendation ITU-R P.676-12 [5] contains algorithms that perform the raytracing through atmospheric layers. For each layer, one first needs to determine the refractive index based on a model of the atmosphere. Here the "high-latitude winter" model as defined in Recommendation ITU-R P.835-6, section 4.2 [6], is chosen for the NOEMA station and the mid-latitude winter model for the IRAM 30 m station, given the geographical latitude of both RAS stations. Additionally, the specific attenuation (also from Recommendation ITU-R P.676-12) of each atmospheric layer is needed to calculate the total attenuation of a “slant path" through the atmosphere. This slant path is usually implemented for cases involving one station (transmitter or receiver) above the earth surface (e.g. in space or at high atmospheric layers), but the same technique can be used for terrestrial paths. If the RAS station and the interfering transmitter are located at very different altitudes, it is more appropriate to use the "slant path" approach. Considering for example radiodetermination devices, which are located in regions at sea level with LOS to the RAS station at high altitude (e.g. 3000 m) the propagation path crosses atmospheric layers of significantly differing physical properties and thus specific attenuation values, which must be considered for an accurate determination of the overall atmospheric loss along the path. Recommendation ITU-R P.676-12 and Recommendation ITU-R P.835-6 contain further details.

To obtain the actual propagation path elevation angles and the regions of LOS cases around each RAS station, one can still use the methods provided in Recommendation ITU-R P.452-16, as these are independent on the observing frequency. For this, topographic (i.e. terrain height) data is needed. For the RAS sites considered in this contribution, there are very precise topographic GIS data sets available, which are based on LIDAR campaigns.

In Figure 13 and Figure 14, topographic maps of the IRAM 30 m and NOEMA observatories are displayed. The regions in direct LOS with respect to the telescopes are shaded in red. For these areas, the free-space basic transmission loss and atmospheric gases absorption loss were calculated as described above. The resulting basic transmission loss[1] are shown in Figure 15 and Figure 16, for two example frequencies, 120 and 140 GHz, which represent a case of very high and relatively low gaseous attenuation, respectively.

[1] Disregarding polarisation coupling loss, scattering in the path, beam spreading loss, multipath loss (radar rays reflected from the ground), clutter loss, building entry loss.

Both attenuation mechanisms are strongly dependent on frequency. For LOS, the loss is proportional to frequency squared. The frequency dependence of atmospheric attenuation, however, is dominated by spectral-line transitions of water and oxygen molecules (see Recommendation ITU-R P.676-12, especially their Figure 4 for details). In the studied frequency range, oxygen produces strong attenuation at 120 GHz (with broad width of several GHz).

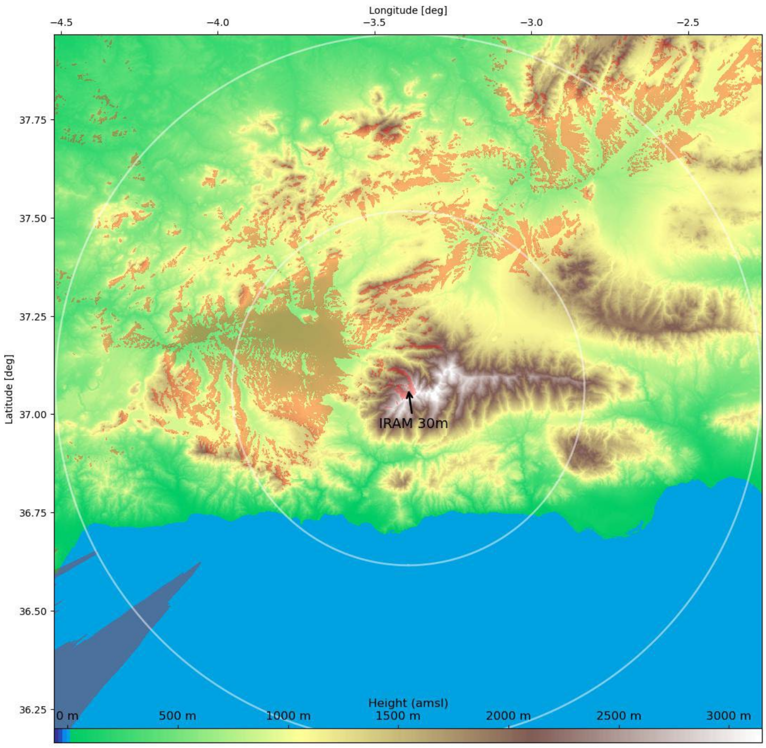


Figure 13: Topographic map of the IRAM 30 m site. The red shaded area shows the line-of-sight regions from the RAS station

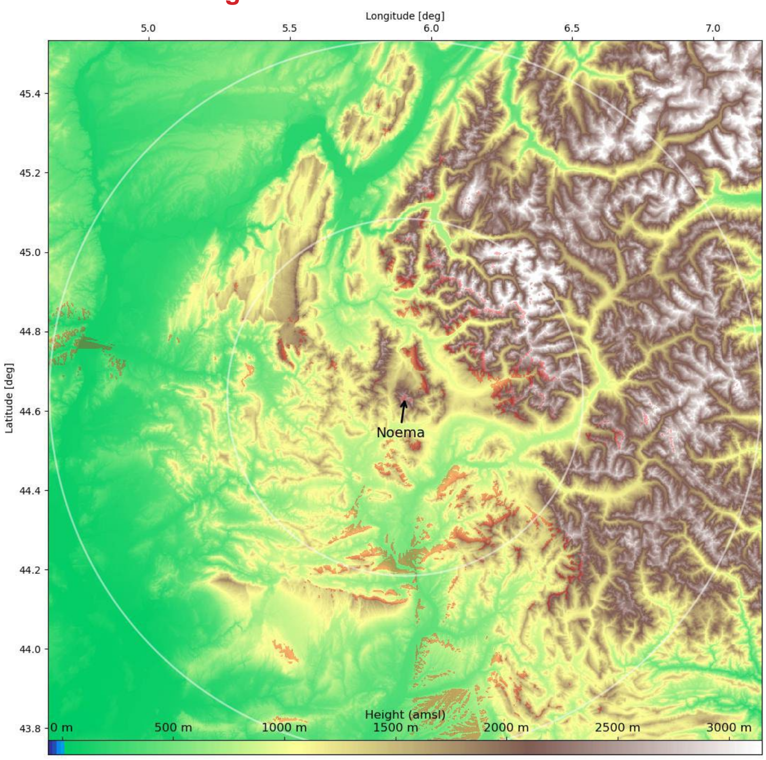


Figure 14: Topographic map of the NOEMA site. The red shaded area visualizes line-of-sight regions from the RAS station

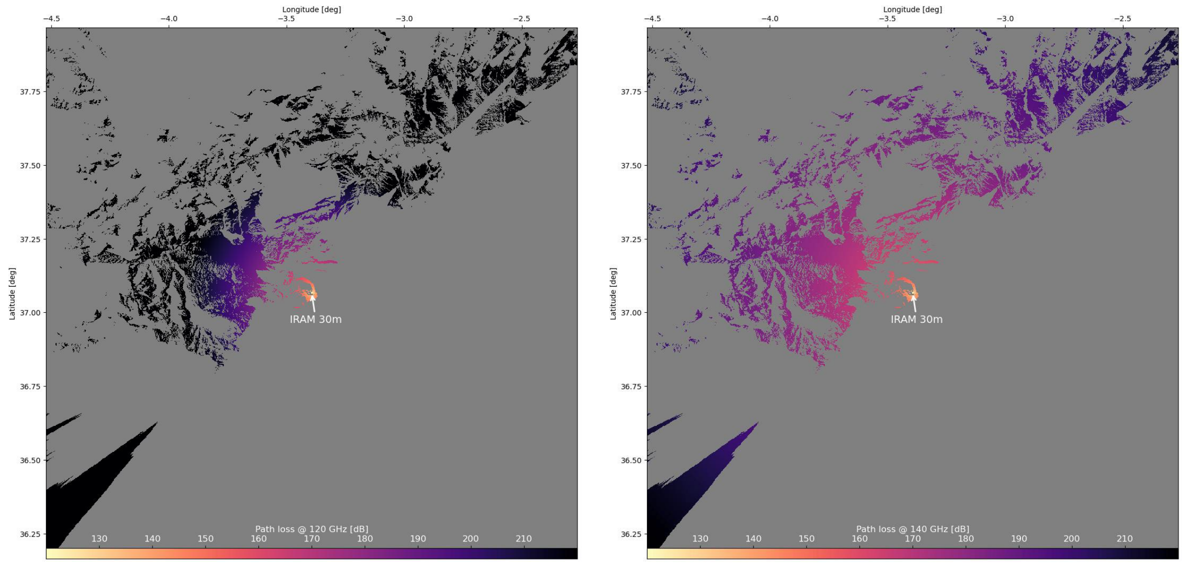


Figure 15: Path attenuation maps for LOS regions around the IRAM 30 m station at 120 and 140 GHz

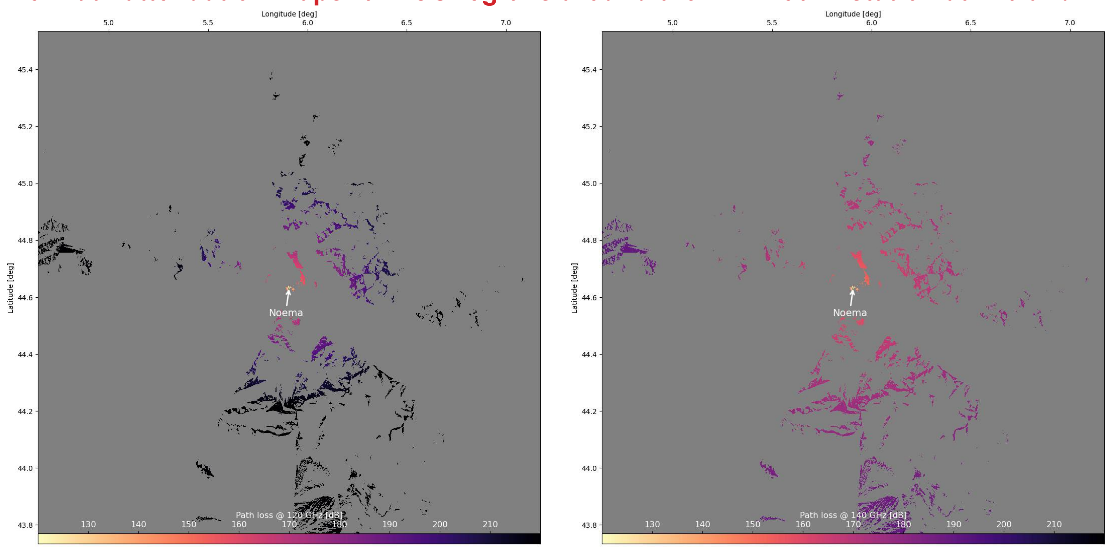


Figure 16: Path attenuation maps for LOS regions around the NOEMA station at 120 and 140 GHz

3.5.2 Separation distances for single-interferer scenario

The difference between the (time-averaged) transmitter e.i.r.p. and the RAS threshold defines the minimal coupling loss (MCL). The difference between the MCL and the path attenuation obtained as described in section 3.5.1 is called the margin. A negative margin means that the RAS thresholds are exceeded (incompatibility), positive margins mean that there is still room before the thresholds are exceeded. A margin of zero indicates a case where the RAS threshold is hit exactly.

3.6 EXTERIOR VEHICULAR APPLICATIONS

In Figure 17 and Figure 18, the zero-margin regions around the two relevant RAS stations, the IRAM 30 m observatory (Spain) and the NOEMA site (France), are shown for three different “effective e.i.r.p.” values associated with the various car radar types (compare Table 14), again for the two example frequency bands at 120 and 140 GHz. The white circles in the figures mark distances from the RAS station in steps of 50 kilometres. The outcome is strongly dependent on the chosen frequency. It is also noted that, as the results were derived under the assumption of a single interferer, some caution is needed when interpreting the results.

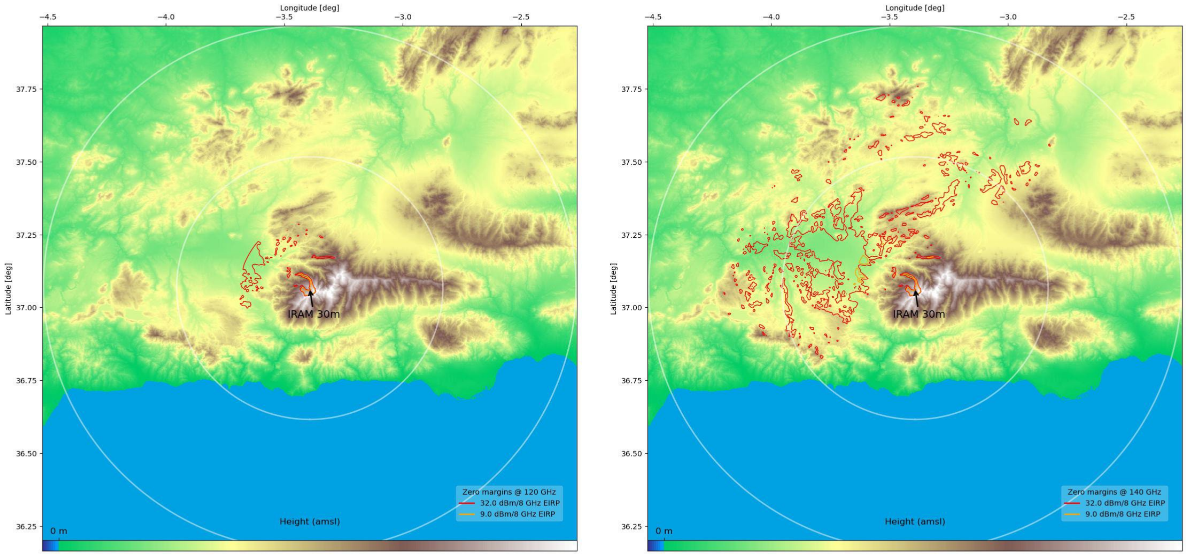


Figure 17: Regions of zero-margin around the IRAM 30 m site for different e.i.r.p. values at 120 and 140 GHz.

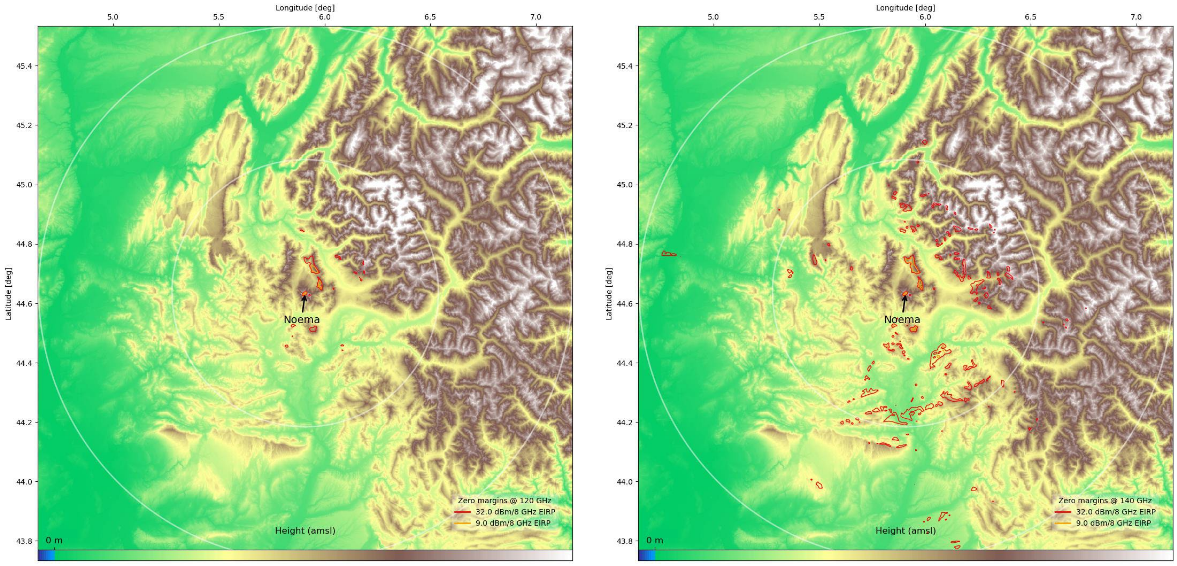


Figure 18: Regions of zero-margin around the NOEMA site for different e.i.r.p. values at 120 and 140 GHz.

It can be observed from Figure 17 and Figure 18, that the zero-margin regions around the two relevant RAS stations are larger for 140 GHz, which can thus be considered as the worst case. This frequency will be used for the rest of the sharing and compatibility study between automotive radars and radio astronomy service.

3.6.1 Results analysis for NOEMA

3.6.1.1 Results analysis for the 9.0 dBm/8 GHz zero-margin lines

For the 9 dBm/8 GHz (orange) zero-margin contour lines, as further elaborated in ANNEX 3, it is concluded that only 2 road sections can be found inside the areas circled by the zero-margin lines. These two road sections are narrow mountain roads with dense clutter (forest), as shown by Figure 82, Figure 83 and Figure 84.

Thus, it is concluded that 9 dBm/8 GHz can be considered as an acceptable power level, without the need for additional protection measures. No risk of interference to Noema RAS site is foreseen for corner and short/ultra-short exterior vehicular radars under such conditions.

3.6.1.2 Results analysis for the 32.0 dBm/8 GHz zero-margin lines

For the 32 dBm/8 GHz (red) zero-margin contour lines, it can be seen in Figure 86 that the risk-of-interference areas are rather remote from each other (several 'clusters'), and they do not form a continuous area. They are distributed over a wider area, and they do happen to overlap with urban areas and roads. An example of such situation is the cluster near Livron and Loriol sur Drome, which is rather small and quite distant from the other ones.

Thus, it is concluded that 32 dBm/8 GHz power level requires additional protection measures to ensure protection of NOEMA RAS telescope. A possible way forward is the introduction of coordination zones, as further discussed in 3.6.4.

3.6.2 Results analysis for IRAM

3.6.2.1 Results analysis for the 9.0 dBm/8 GHz zero-margin lines

For the 9 dBm/8 GHz (orange) zero-margin contour lines, as further elaborated by Figure 97, it can be seen that there are only two risk-of-interference areas: the east side of Granada city and the vicinity of IRAM. Furthermore, the zero-margin contour lines for 6.0 dBm/8 GHz (blue lines) appear only in the vicinity of the IRAM telescope, showing that such power level would not be an issue for the city of Granada. In the vicinity of the IRAM telescope, it appears that the -6 dBm/8 GHz (teal) contour lines reduced to only one area of interest which includes two roads with dense clutter, which can therefore be considered as an acceptable power level generating no significant interference toward the RAS.

Thus, it is concluded that 9 dBm/8 GHz power level requires additional protection measures to ensure protection of IRAM RAS telescope. A possible way forward is to introduce coordination zones, as further discussed in 3.6.4, potentially using the 6 dBm/8 GHz power level which appears to be an acceptable power level for the east side of the city of Granada.

3.6.2.2 Results analysis for the 32.0 dBm/8 GHz zero-margin lines

For the 32 dBm/8 GHz (red) zero-margin contour lines, it can be seen from Figure 97 that the risk-of-interference areas are distributed over a wide area, and they do happen to overlap with urban areas and roads.

Thus, it is concluded that 32 dBm/8 GHz power level requires additional protection measures to ensure protection of IRAM RAS telescope. A possible way forward is the introduction of coordination zones, as further discussed in 3.6.4.

3.6.3 Immediate Vicinity of the RAS and associated exclusion zone

Radio astronomy community indicated the need to protect the immediate vicinity of both telescopes (3 km radius around the RAS) with a very stringent power limit (ideally a switch-off), since it is possible that people would drive cars up to the telescope even in absence of roads or bring cars up to the RAS using cable car.

Thus, both for NOEMA and IRAM RAS, one exclusion zone is defined with radius of 3 km centred on the RAS is defined to ensure protection of the immediate vicinity of the RAS.

An exclusion zone is defined as a geographical area (typically the area within a circle) within which the transmit operation of the radar equipment is automatically disabled (without manual intervention from the driver of the vehicle) to ensure no disturbance is generated towards a RAS in immediate vicinity.

3.6.4 Coordination zones proposal

3.6.4.1 Methodology

Single-interferer scenario simulations have been conducted for both NOEMA and IRAM RAS sites. Results show the need for additional measures to ensure protection of NOEMA telescope for exterior vehicular radars with transmit powers of 32 dBm/8 GHz, and the need for additional measures to ensure protection of IRAM telescope for exterior vehicular radars with transmit powers of 9 or 32 dBm/8 GHz. Coordination zones are identified as a way forward.

A coordination zone is defined as a geographical area (typically the area within a circle) within which the transmit parameters (e.g. duty cycle and/or transmit power) of a radar equipment are automatically adapted (without manual intervention from the driver of the vehicle) to ensure an acceptable level of disturbance is generated towards a RAS nearby.

One or several coordination zones may be defined to protect a given RAS station, and such zones can be defined disjoint ('clusters approach') or such zones may overlap ('nested approach'). Usage of several coordination zones allows having a finer granularity and allows reducing the overall area impacted. This may be a way to avoid having large metropolitan areas or motorways inside coordination zones, thereby allowing such areas to benefit from automotive radar systems for advanced driver assistance systems.

3.6.4.2 Coordination zones proposal for NOEMA

For NOEMA, four coordination zones design options are detailed in ANNEX 3.

Option 4 is the recommended solution, as illustrated by Figure 19. It defines ten coordination zones, which allows to remove some large metropolitan areas (e.g. Grenoble, Valence and Gap) or important highways (e.g. A7) from coordination zones. The coordination zone(s) details are provided in Table 44.

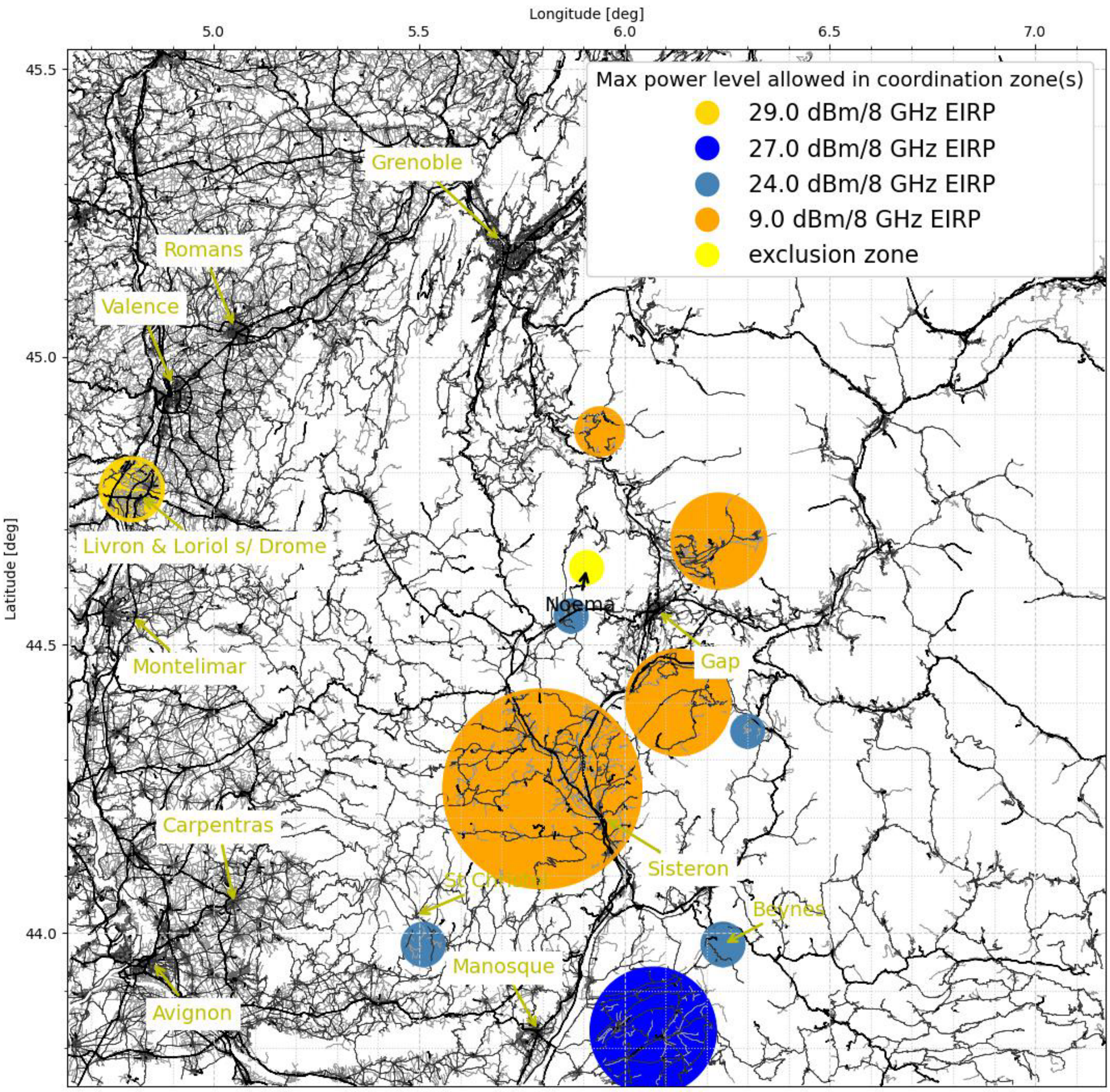


Figure 19: NOEMA, coordination zone summary, option 4

3.6.4.3 Coordination zones proposal for IRAM

For IRAM, three coordination zones design options are detailed in ANNEX 3.

Option 3 is the recommended solution, as illustrated by Figure 20. It defines four coordination zones, which allows removing some large metropolitan areas (e.g. Jaen, Costa Tropical de Granada, west part of Granada) or important highways (e.g. A-7, A-92 and A-44) from coordination zones. An intermediate maximum power level limitation of 17 dBm/8 GHz (15 dB down from front radar power) is introduced to relax constraints for the outermost part of the big zone. The west part of Granada and west of A-92, A44 are under the maximum power limitation of 9 dBm/8 GHz (corner and short radar power), while the east side of Granada has a maximum power level of 6 dBm/8 GHz (3 dB down from corner and short radar power), and the IRAM vicinity a maximum power level of -6 dBm/8 GHz. The coordination zone(s) details are provided in Table 50.

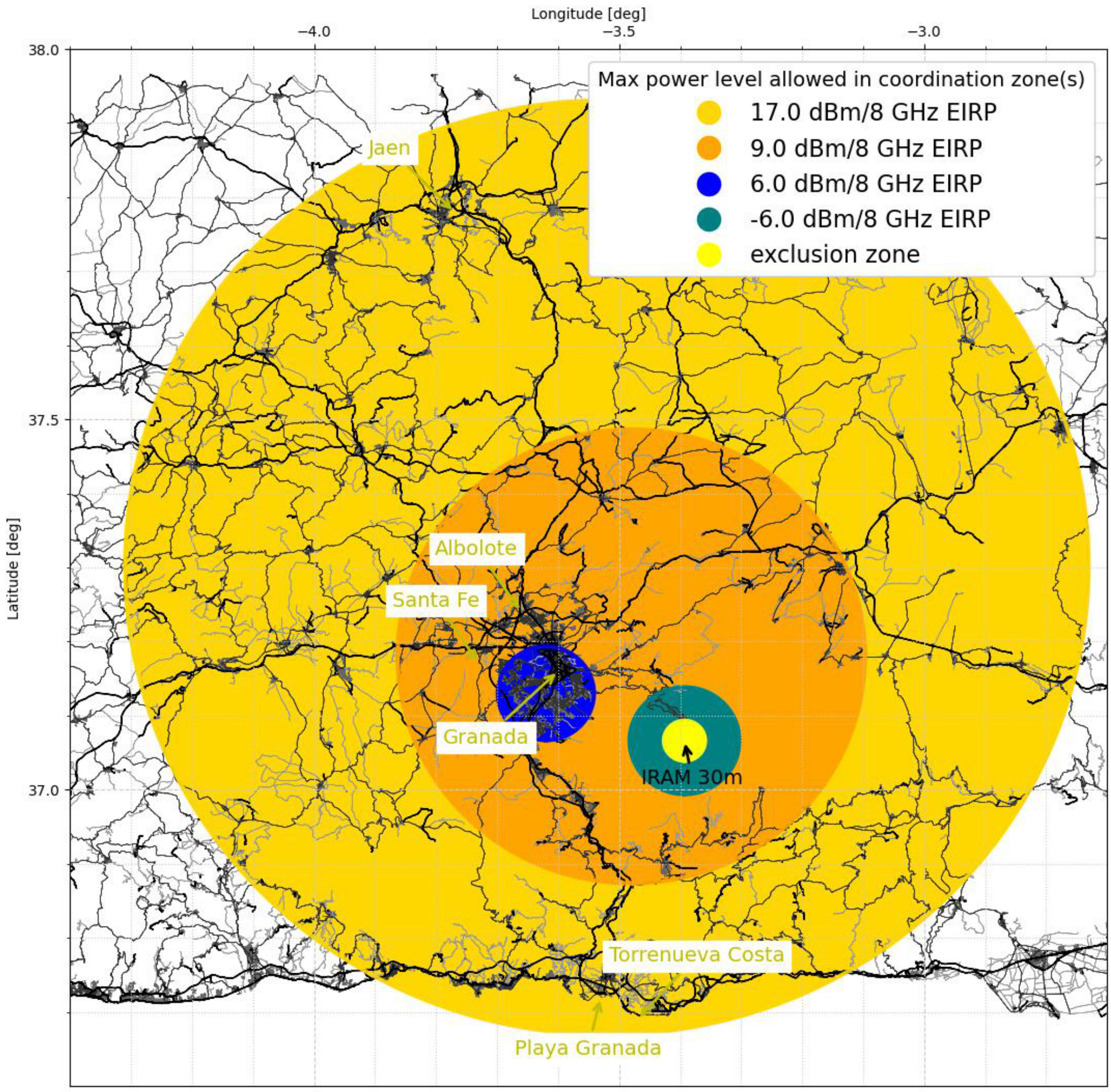


Figure 20: IRAM, coordination zone summary, option 3

3.7 IN-CABIN VEHICULAR APPLICATIONS

In Figure 21 and Figure 22, the zero-margin regions for the two relevant RAS stations, IRAM 30 m observatory (Spain) and the NOEMA site (France), for interference with single in-cabin vehicular radar are presented. The simulation was conducted for effective radiated power into RAS band of -12 dBm (mean e.i.r.p. of 3 dBm and 15 dB of exit-loss). Two example frequencies are presented: 120 GHz and 140 GHz. The red line indicates the zero-margin region, the white circles in figures mark distances from RAS stations in steps of 50 km. The results were derived under assumption of a single interferer.

The calculated regions of zero margin for RAS stations IRAM 30 m in Spain and NOEMA in France are very limited and include only direct vicinity of both radio stations. No public roads or residential areas are located within the zero margin areas. However, in order to ensure protection of RAS stations it is proposed to define an exclusion zone in direct vicinity of each of radio station.

Radio telescope community indicated the need to protect the immediate vicinity (e.g. 3 km radius around the RAS) of both telescopes with a very stringent power limit (ideally a switch-off), since it is possible that people would drive cars up to the telescope even in absence of public roads or bring cars up to the RAS using cable car.

An implementation of an automatic system to disable transmission of in-cabin radar devices coupled with geo-positioning of the vehicle, referred as “exclusion zone”, should be considered in order to protect immediate vicinity of each RAS station. An exclusion zone is defined as a geographical area (typically the area within a circle with e.g. 3 km radius) within which the transmit operation of the radar equipment is automatically disabled (without manual intervention from the driver of the vehicle) to ensure no disturbance is generated towards a RAS in immediate vicinity.

The study shows that additional separation distances, beside exclusion zones in direct vicinity of RAS stations, are not needed between in-cabin vehicular radar and observatories NOEMA in France and IRAM 30 m in Spain.

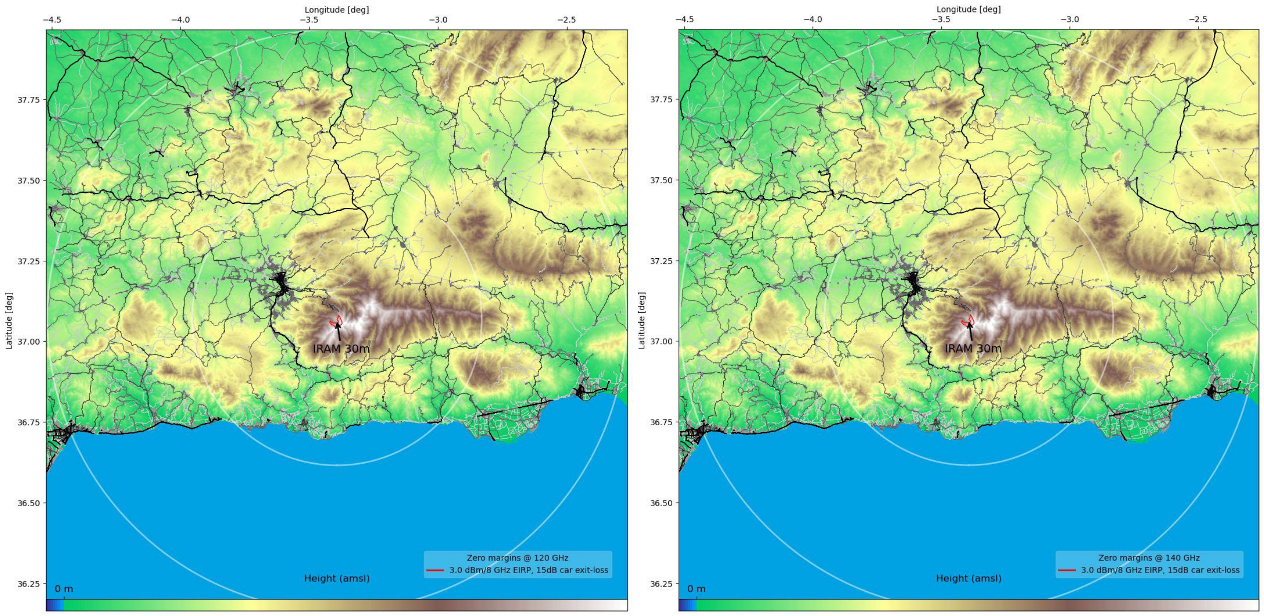


Figure 21: Region of zero-margin around IRAM site for in-cabin radar at 120 and 140 GHz

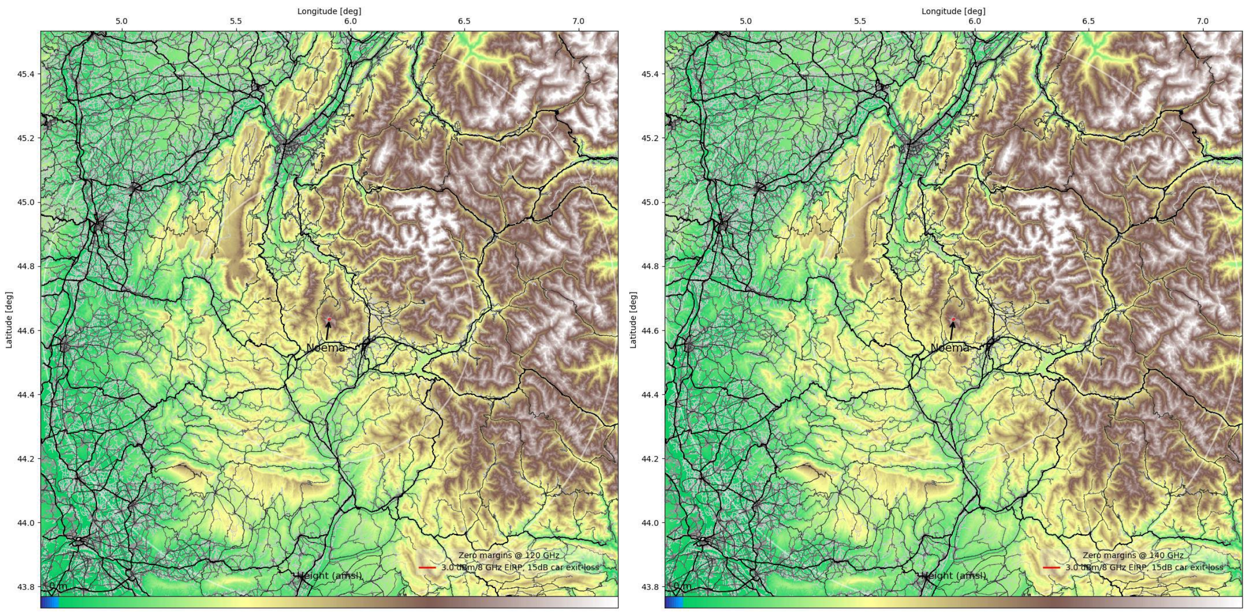


Figure 22: Region of zero-margin around NOEMA site for in-cabin radar at 120 and 140 GHz

4 SHARING AND COMPATIBILITY STUDIES WITH FIXED SERVICE

4.1 FIXED SERVICE (FS) TECHNICAL PARAMETERS AND PROTECTION CRITERIA

Fixed service (FS) systems are used in telecommunication networks in various situations, e.g. for:

- Transport networks (trunking, multi-hop and long-haul connections);
- Mobile backhaul networks;
- Fixed wireless access (FWA) systems;
- Temporary networks (e.g. for disaster relief or electronic news gathering).

Significant recent and ongoing increases in data traffic have led to the requirement for network services of being capable of supporting very high data rates. A consequence of these evolution has been an increased use of new higher frequency bands by FS for shorter distances since higher frequencies are associated with wider bandwidths, higher capacity and smaller antenna dimensions. Consequently, there is increasing interest in the 60 GHz (57-64 GHz) and in the 70 to 80 GHz (71-76 GHz and 81-86 GHz) bands (see Report ITU-R F.2323-0 [17]). Even some applications operating in the frequency band above 275 GHz such as the point-to-point backhaul and fronthaul for mobile services are introduced and the ultra-high-speed data transmission between fixed stations become feasible.

The technical parameters and protection criteria for Fixed Services (FS) in the frequency ranges from below 1 GHz up to the bands 71-76 GHz and 81-86 GHz can be found in Recommendation ITU-R F.758-7 [18]. For the higher frequency range from 275-450 GHz Report ITU-R F.2416-0 [19] may be consulted. For the frequency range from 116 to 260 GHz, the protection criteria and service parameters in sections 4.1.1 and 4.1.2 are considered.

4.1.1 Protection criteria

In order to assess the impact of radio determination on the FS, it is proposed to adopt the following protection criteria:

- A long-term protection criterion of I/N = -20 dB (see ITU-R Recommendation F 758-7, table 4 [18]) for non co-primary services not to be exceeded for more than 20% of time;
- Beside the long-term criterion for all UWB applications an I_{peak}/N < +5 dB should be considered[2].

The determination devices are continuously emitting; therefore, the short-term criteria are not relevant.

These protection criteria are based on the definitions in Report ITU-R SM.2057, pages 324-327 [2].

The peak criterion allows for 25 dB higher interference compared to the long-term criterion. Since the studied peak emission levels for the vehicular radars are only 5 dB higher than the considered radiated mean emission levels, the margin towards the peak criterion will always be a 20 dB margin compared to the chosen method evaluation against the long-term criterion. Hence, the peak criterion will not impact the end results.

4.1.2 Fixed service parameters

Parameters valid for the bands 71-76 GHz/81-86 GHz, have been reviewed and the parameters in Table 17 have been agreed to be taken into account for the studies.

[2] Originallly, the peak criterion was defined in 50 MHz but current FS systems operate in a much higher bandwidth. Therefore, the criterion is evaluated over the bandwidth of the FS receivers.

Table 17: FS parameters in the frequency range 71−260 GHz

System parameter	71-86 GHz (E-band)	92-114.25 GHz (W-band)	130-175 GHz (D-band)	175-260 GHz	References
Receiver noise figure (dB)	10	12	14	16	Extrapolated from Recommendation ITU-R F. 758-7 [18] (for 80 GHz)
Receiver noise power density typical (dBW/MHz)	-134	-132	-130	-128	
Channel bandwidth	Nx250 MHz up to 5 GHz (noting that current regulation does not set any upper limit for BW)				Extrapolated from ECC Recommendation (18)01 [21] and ECC Recommendation (18)02 [22]
Antenna losses (dB)	0−3				Extrapolated from Report ITU-R F.2416 [19]
Antenna gain (dBi)	24−50				
Antenna class	2/3				Extrapolated from the 80 GHz band in ETSI EN 302 217-4 [27]
Antenna height (m)	6 (light pole/Kiosk) to 25 (rooftop) (note 1)				Extrapolated from Report ITU-R F.2416 [18]
Antenna elevation (degrees)	Typically, less than ±20 (note 2)				

Note 1: The antenna heights in the urban area are estimated to be in the range 6-25 m.

Note 2: In order to take into account the different urban areas around the world, it is assumed that a typical elevation would be less than ±20 degrees. The elevation angles of the antenna are calculated from the antenna height of FS stations and the distance between FS links. Although the distance between the base stations in the dense urban area is also indicated to be 200 m, the distance range of 100-300 m is assumed to be used for calculation of elevation angle of antenna.

ECC Report 282 [20] provides additional information about FS systems in these ranges.

In particular, ECC Recommendation (18)01 [21] contains specific channel arrangements for the FS allocated bands within the range 130-174.8 GHz and ECC Recommendation (18)02 [22] for the range 92-114.25 GHz.

ITU-R WP 5C is studying for extending the applicability of antenna reference radiation patterns above 86 GHz, in order to possibly update Recommendation ITU-R F.699-8 [23] and Recommendation ITU-R F.1245-3 [24], which provide reference radiation patterns to be used for coexistence studies.

For the time being indoor applications are considered potentially possible, but in very specific and limited cases (see ECC Report 282, section 6.3).

The antenna pattern is based on Recommendation ITU-R F.699-8 extending the antenna pattern valid in the frequency range 70-86 GHz to the frequency range considered in this Report, due to lack of more relevant antenna patterns.

4.2 INTERFERENCE SCENARIOS

The typical scenario in which an interference signal propagates along a terrestrial path is relevant. In this case, sensor installations might have an impact on the victim stations through direct emissions emitting in horizontal direction along the earth's surface, due to the fact that vehicles can have any orientation in the azimuth direction, therefore can radiate in any direction. Thus, the case where the main beam direction of the radar points exactly towards the antenna of the victim service should be considered as the worst-case.

The interference scenarios have been developed describing a typical situation in urban environments where a Fixed Service transmitter attached to a light pole is linked with a receiver located on top of a building and vice versa (see Figure 23 and Figure 24).

4.2.1 Scenario 1 - FS receiver on the building

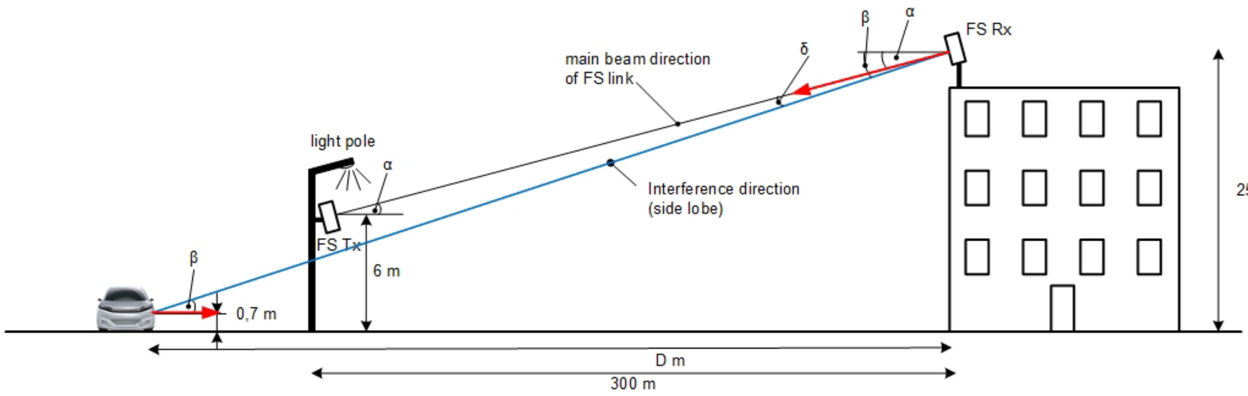


Figure 23: Light pole connected to a building by means of an FS link – FS Rx on building

In the first scenario (see Figure 23) the vehicle is aligned towards the FS receiver on the top of the building.

4.2.2 Scenario 2 - FS receiver at the light pole

In the second scenario (see Figure 24) the building rooftop is again connected to a light pole. In contrast to the first scenario, the locations of the FS Rx and the FS Tx are exchanged. The distance between the FS Rx and Tx is again 300 m and the vehicle is aligned towards the FS receiver on the light pole.

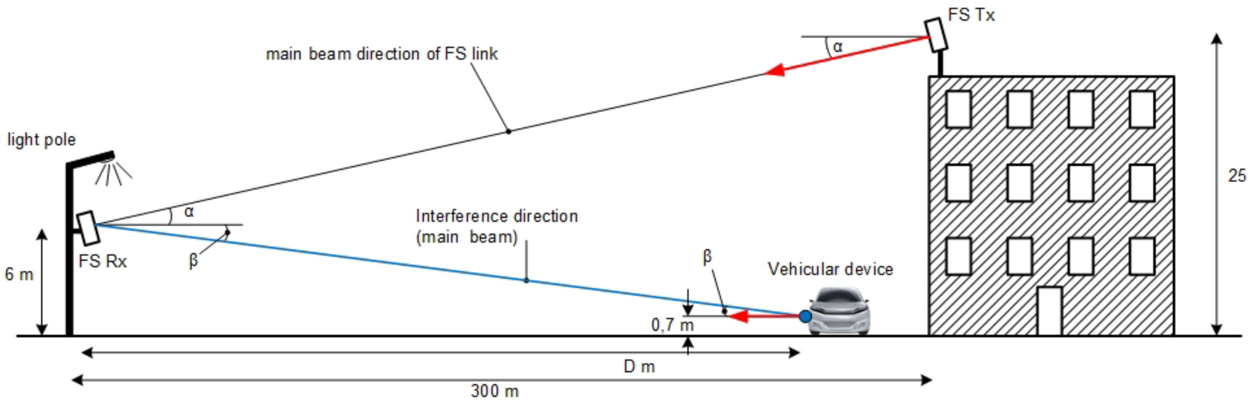


Figure 24: Light pole connected to a building by means of an FS link – FS Rx at light pole

4.2.3 Scenario 3 - FS receiver on the building with extra reflection

Within the urban environment there could be interference scenarios based on multi-path / reflection. To consider such interference scenarios in Figure 23 was adjusted to consider reflection at a building (see Figure 25).

Currently there is only a very low amount of information regarding the attenuation based on reflections in these high frequency ranges available. Based on the literature [30], for the calculations an attenuation of 8 dB was considered.

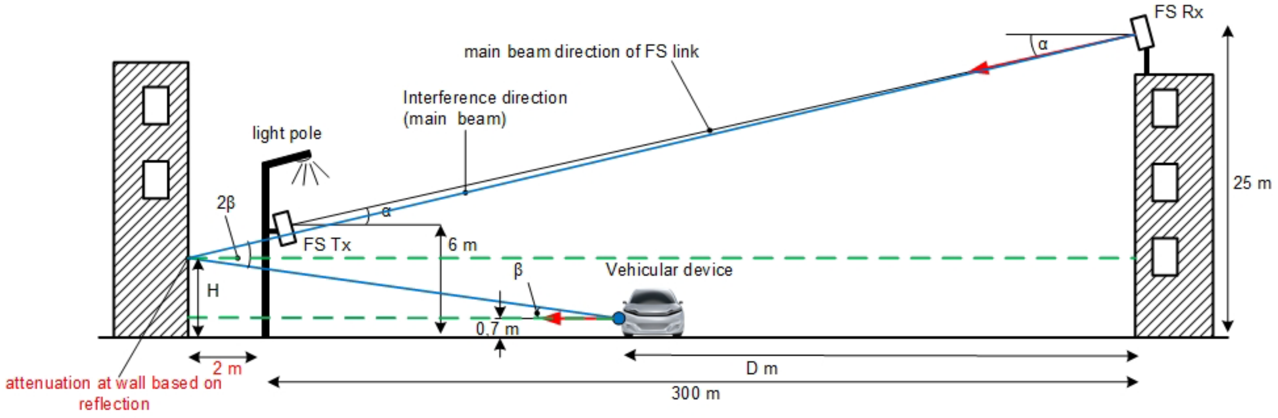


Figure 25: Light pole connected to a building by means of an FS link – FS Rx on building and indirect interfering path

4.3 RESULTS FOR EXTERIOR VEHICULAR RADARS

4.3.1 Technical parameters

For the automotive surveillance radar equipment three potential frequency bands have been defined (see section 2.1.2 and Figure 2).

Due to the fact that in all defined frequency bands allocations for FS are affected –either within these bands or adjacent to them– all three bands have been investigated by single entry studies. In these studies is determined by means of the technical parameters (see section 2.1.3), the interference scenarios (see section 4.2) and the protection requirements for FS (see section 4.1.1). The exact calculations can be found in the Excel-spreadsheet attached to this Report.

4.3.2 Interference scenarios-specific considerations

Under the worst-case assumptions within the single entry case, the vehicle is directly below the FS-link without misalignment in the azimuth (horizontal plane) (see Figure 26). In this situation, only the elevation pattern of the automotive radar types needs to be considered. Given that corner and short-range radars have the same elevation pattern (see section 2.1.3.1), the studies for those radars can be merged.

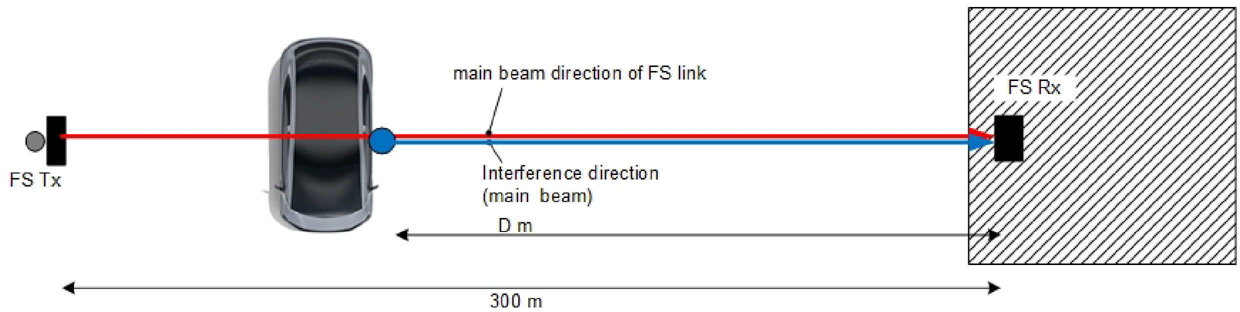


Figure 26: Aerial view of the interference scenarios

Given that the typical Duty Cycle of the automotive radars is larger than 20%, no DC mitigation was considered in the worst-case single entry studies.

This consideration led to the following single entry investigations which were made for all three interference scenarios:

- In-band case of vehicular radar (long-range and corner/short) within 141-148.5 GHz;
- Adjacent cases at the frequency 141 GHz, 134 GHz and 130 GHz. Based on the same protection requirement of FS within the FS bands (130-134 GHz and 141-148.5 GHz) the studies were limited to one frequency (adjacent emission into 141-148.5 GHz).

4.3.3 Results

Within the interference scenarios, the vehicle could be positioned anywhere on the line between the FS transmitter and receiver. Any points on this line where the protection margin is negative indicate that the FS receiver could experience interference.

4.3.3.1 Results single entry in-band case (automotive radar in 141-148.5 GHz)

Figure 27 shows the result for a long-range and a corner/short-range radar with a bandwidth of 1 GHz in scenario 1 (see Figure 23). Both FS protection requirements (peak and long term) were calculated.

For the automotive radar, the following parameters were assumed:

- Front radar: 40 dBm peak power e.i.r.p. (35 dBm mean power e.i.r.p.), 1 GHz bandwidth and antenna pattern A (see section 2.1.3.1) with maximum 30 dBi gain;
- Corner and short/ultra-range radar: 20 dBm peak power e.i.r.p. (15 dBm mean power e.i.r.p.), 1 GHz bandwidth and antenna pattern C (see section 2.1.3.1) with maximum 23 dBi gain.

These are summarised in Table 18.

Table 18: Automotive radar assumptions

Parameter	Front radar	Corner and short/ultra-short range radar
Peak e.i.r.p.	40 dBm	20 dBm
Mean e.i.r.p.	35 dBm	15 dBm
Bandwidth	1 GHz	1 GHz
Antenna pattern	"Pattern A"	"Pattern C"
Max. antenna gain	30 dBi	23 dBi

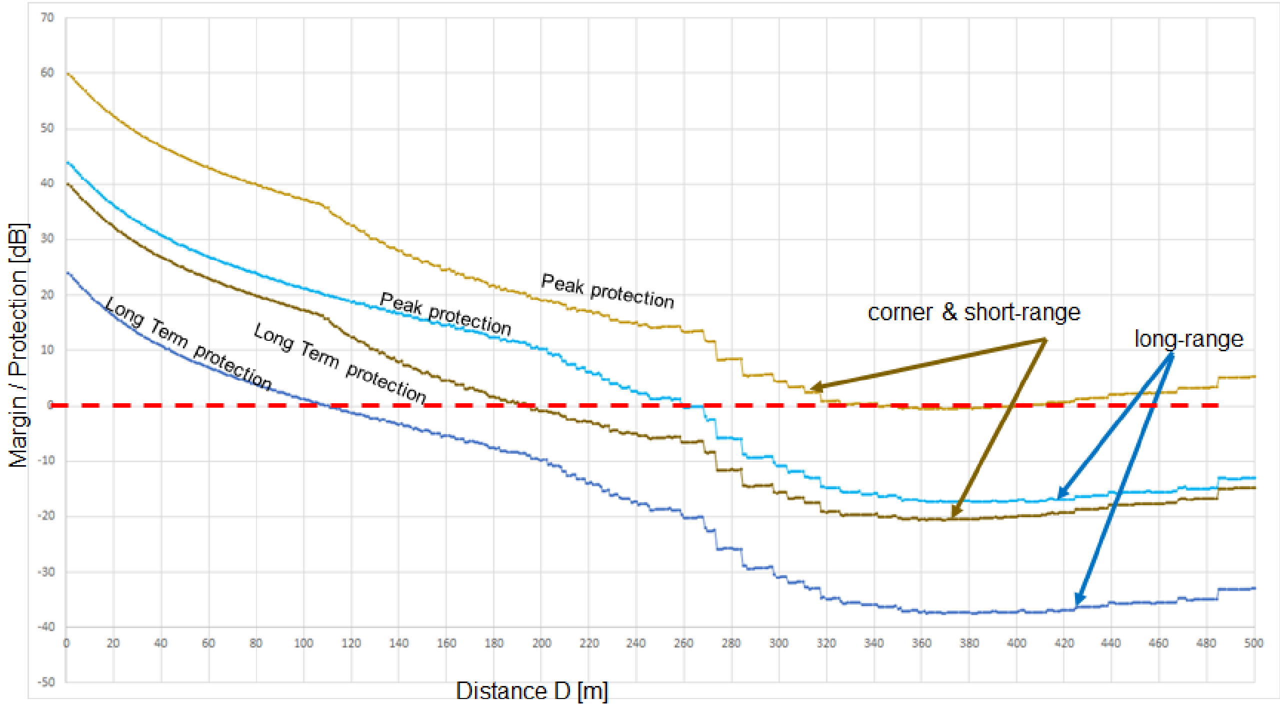


Figure 27: In-band single entry assessment on protection margin of FS for long range and corner/short range radar in scenario 1

To assess the impact of the bandwidth of the corner and short/ultra-short range radar, the evaluation is repeated with the following parameters summarised in Table 19:

- Corner and short/ultra-short range radar: 20 dBm peak power e.i.r.p. (15 dBm mean power e.i.r.p.), 1 GHz/2 GHz/4 GHz/7 GHz BW, a maximum allowed mean power density and antenna pattern C (see section 2.1.3.1) with maximum 23 dBi gain

Table 19: Modified automotive radar assumptions

Parameter	Corner and short/ultra-short range radar
Peak e.i.r.p.	20 dBm
Mean e.i.r.p.	15 dBm
Bandwidth	1 / 2 / 4 / 7 GHz
Antenna pattern	"Pattern C"
Maximum antenna gain	23 dBi

Based on the calculation shown in Figure 27 only the more critical long-term protection requirement for FS was considered.

The results are shown in Figure 28.

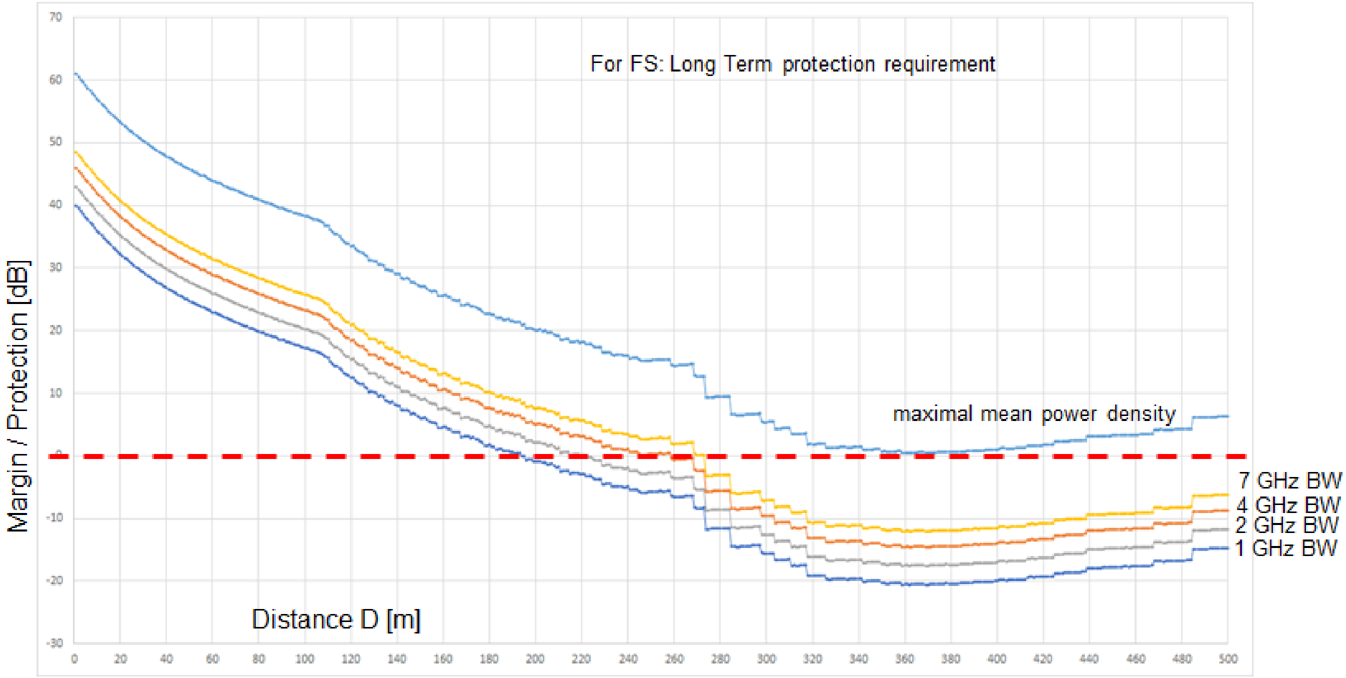


Figure 28: n-band single entry assessment on protection margin of FS for corner/short range radar and different BW in scenario 1

For all proposed bandwidths, the protection criterion is not met under these conditions. With a mean power spectral density of -36 dBm/MHz, the protection criterion is met.

Similar to the calculation for Figure 27 same calculations for scenario 2 (Figure 24) and scenario 3 (Figure 25) provided following results. Scenario 2 can be found in Figure 29 and scenario 3 can be found in Figure 30.

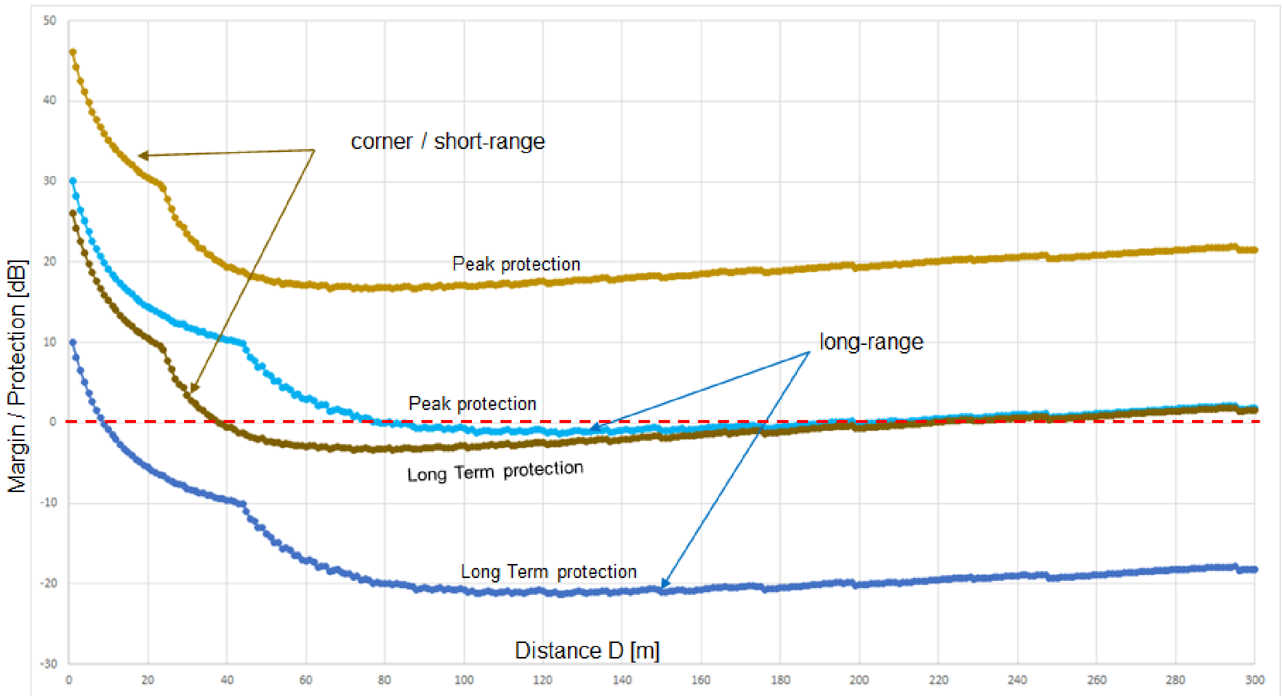


Figure 29: In-band single entry assessment on protection margin of FS for long range and corner/short range radar in scenario 2

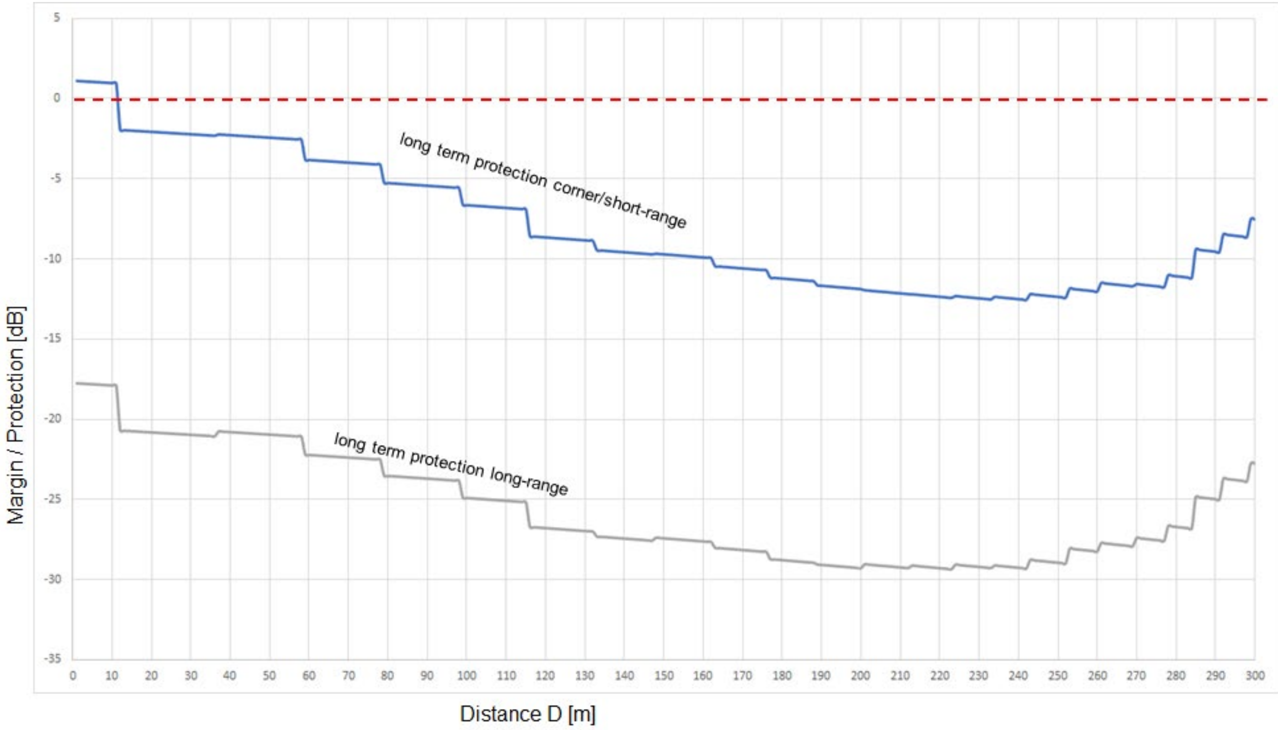


Figure 30: In-band single entry assessment on protection margin of FS for long range and corner/short range radar in scenario 3

Summary single entry for the in-band case:

- Interference scenario 1 is the most critical one.
- FS would be protected in scenario 1 with the following radiation parameters:
  - Mean power spectral density of -36 dBm/MHz e.i.r.p.;
  - A maximum mean e.i.r.p. of -6 dBm within 1 GHz;
  - A maximum peak e.i.r.p. of -1 dBm within 1 GHz.

4.3.3.2 Results single entry adjacent case (automotive radar below 141 GHz - FS above 141 GHz)

Given that the in-band studies show that scenario 1 is the most critical one, the adjacent band was first assessed for this scenario. Then it was verified that the resulting power levels also protect FS in scenarios 2 and 3.

For the calculation, the following assumptions were made:

- The limit within the FS range is minimum 20 dB below the mean power density limit in-band;
- The BW of the automotive radar (in-band) is 1 GHz;
- The antenna pattern of the automotive radar in the unwanted domain of the radar is similar to the in-band pattern.

The results for the adjacent case at 141 GHz are shown in Figure 31.

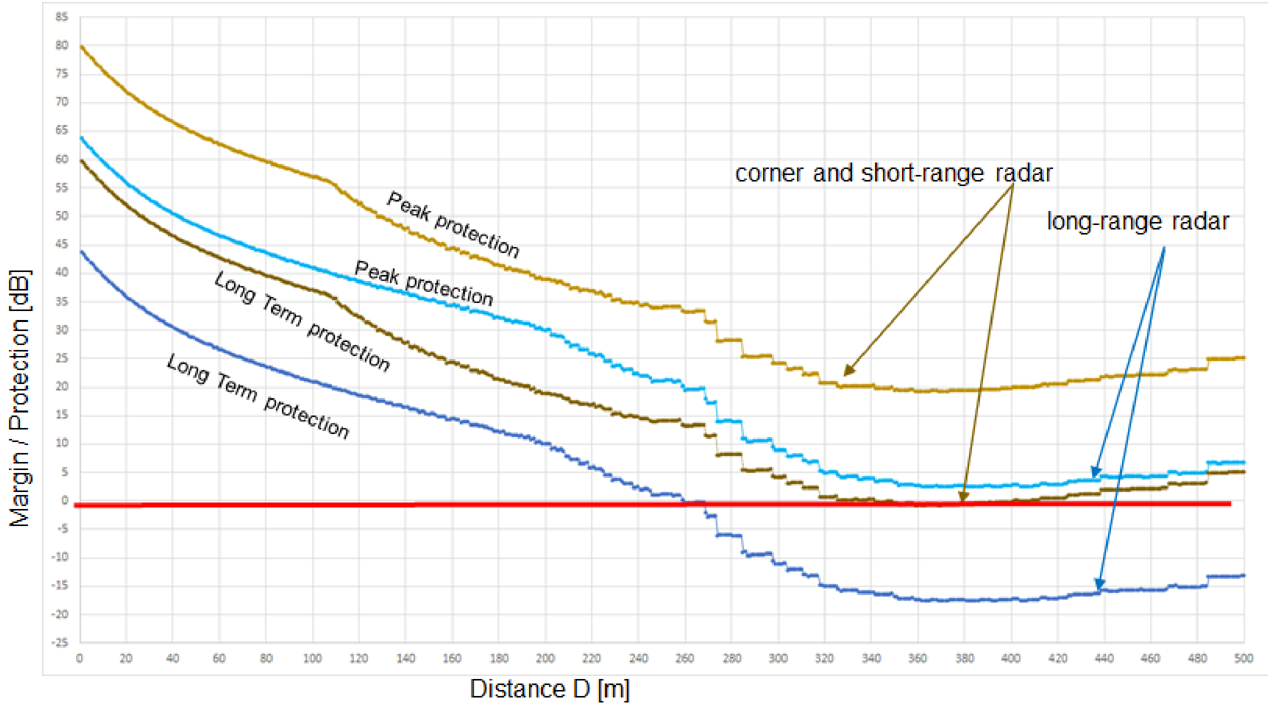


Figure 31: Adjacent band single entry assessment at 141 GHz on protection margin of FS for long range and corner/short range radar in scenario 1

The calculations show that the definition of the BW of the automotive radar (OOB 20 dB below) is not sufficient to protect FS in all cases. Therefore, it was calculated which out-of-band power level is necessary to protect FS from automotive radar in the adjacent band. For more information see section 2.1.3.2.

This consideration for the FS case and the use of a possible guard range is shown in Figure 32.

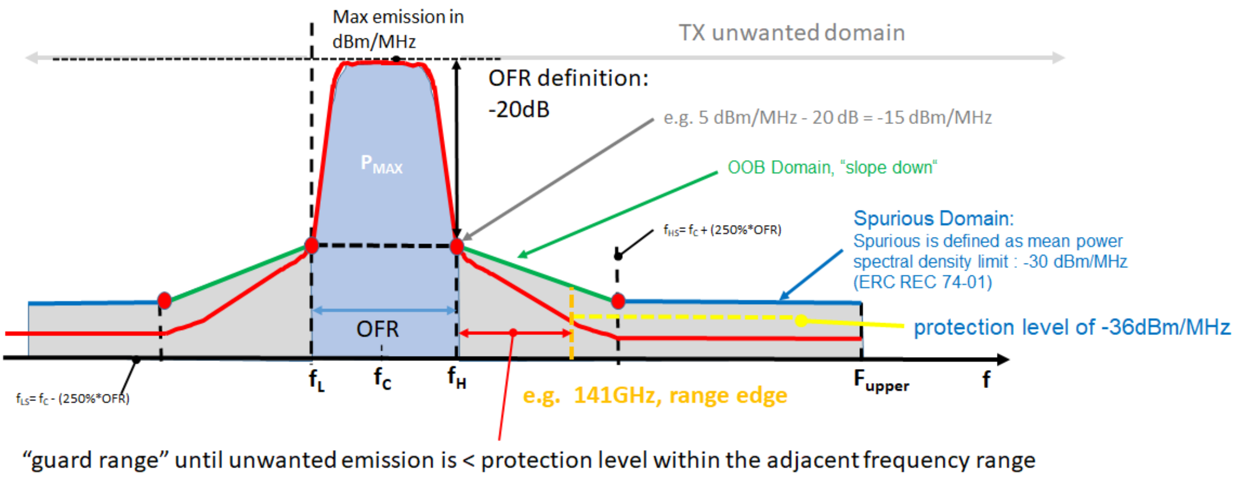


Figure 32: Consideration on guard range

Figure 33 shows the result for a long-range automotive radar below 141 GHz and a mean power spectral density limit in the FS range of -33/-36dBm/MHz

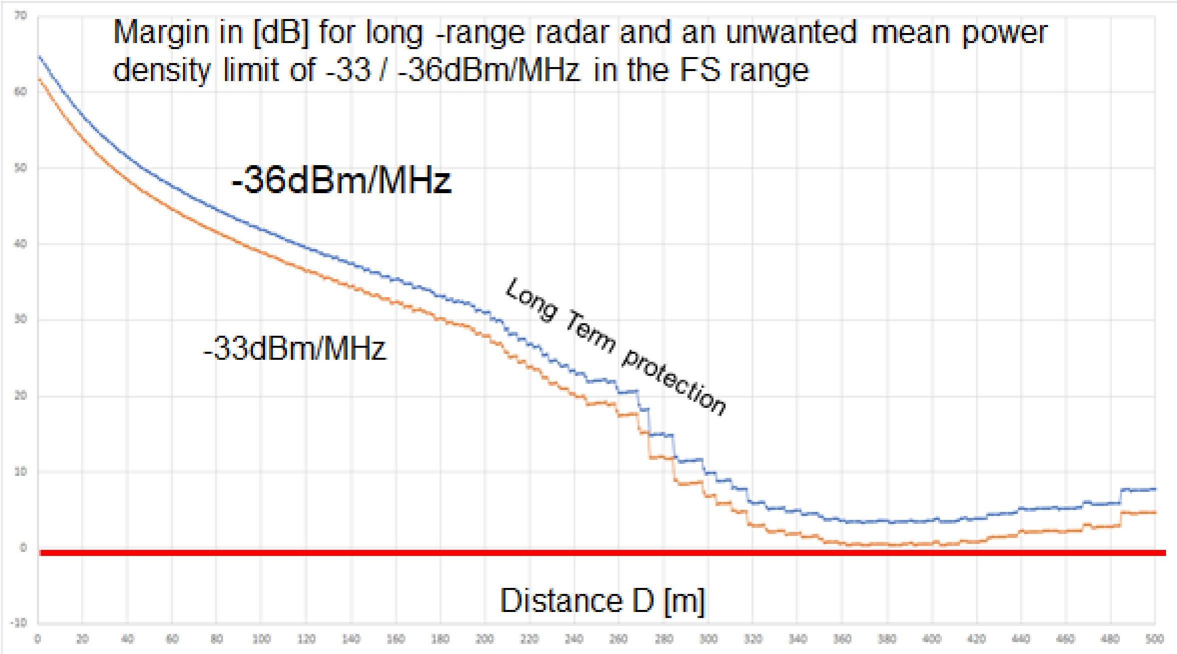


Figure 33: Protection margin for FS based on long range radar unwanted emissions within FS range (above 141 GHz)

Similar to the adjacent single entry assessment of scenario 1 the assessments of scenario 2 (see Figure 34) and scenario 3 (see Figure 35) show that scenario 1 is the most critical one.

For scenario 2, a level of -33 dBm/MHz e.i.r.p. within the FS band provide a positive margin of minimum 17 dB of protection. Therefore, the same out-of-band /spurious limit in the adjacent (within the FS) of -33 dBm/MHz (see Figure 34) will not cause any interference issue in the single entry case comparison with the result out of scenario 1 (see Figure 33).

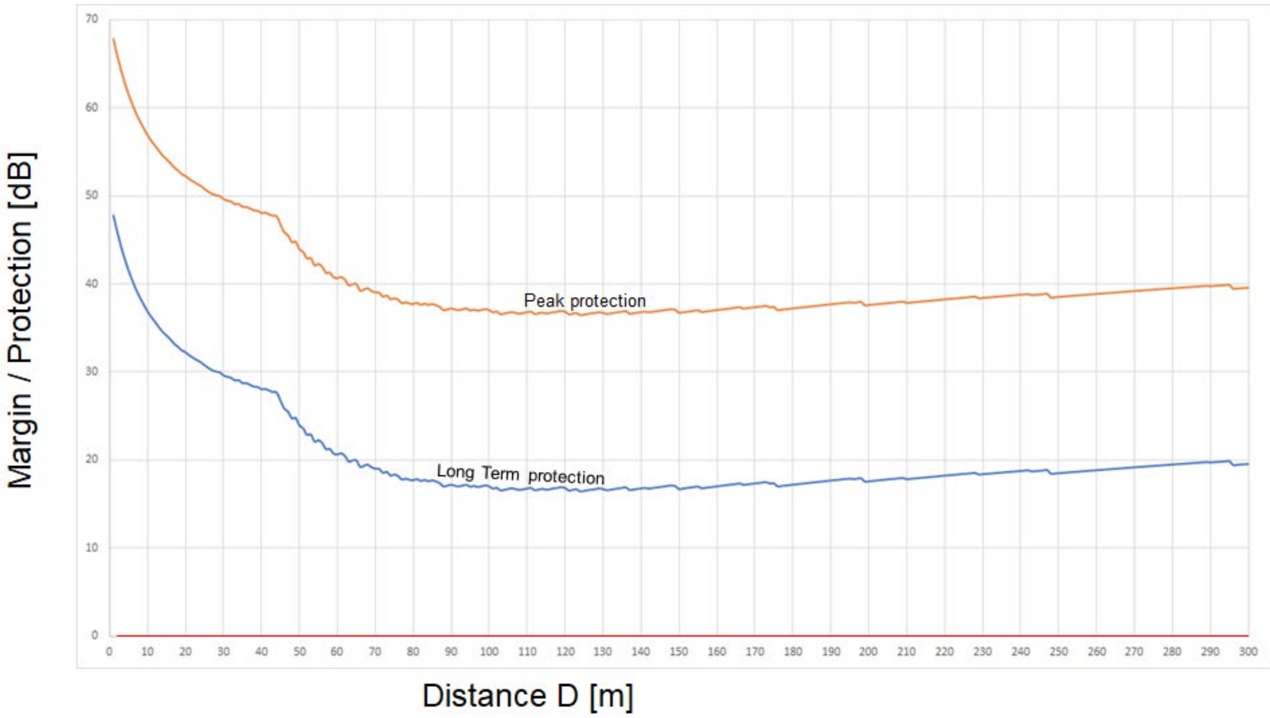


Figure 34: Protection margin for FS scenario 2 in the adjacent case and a front radar with unwanted emissions of -33 dBm/MHz e.i.r.p. within FS range

For scenario 3, a level of -33 dBm/MHz e.i.r.p. within the FS band provide a positive margin of minimum 8 dB of protection. Therefore, the same out-of-band /spurious limit in the adjacent (within the FS) of -33 dBm/MHz (see Figure 35) will not cause any interference issue in the single entry case in comparison with the result out of scenario 1 (see Figure 33).

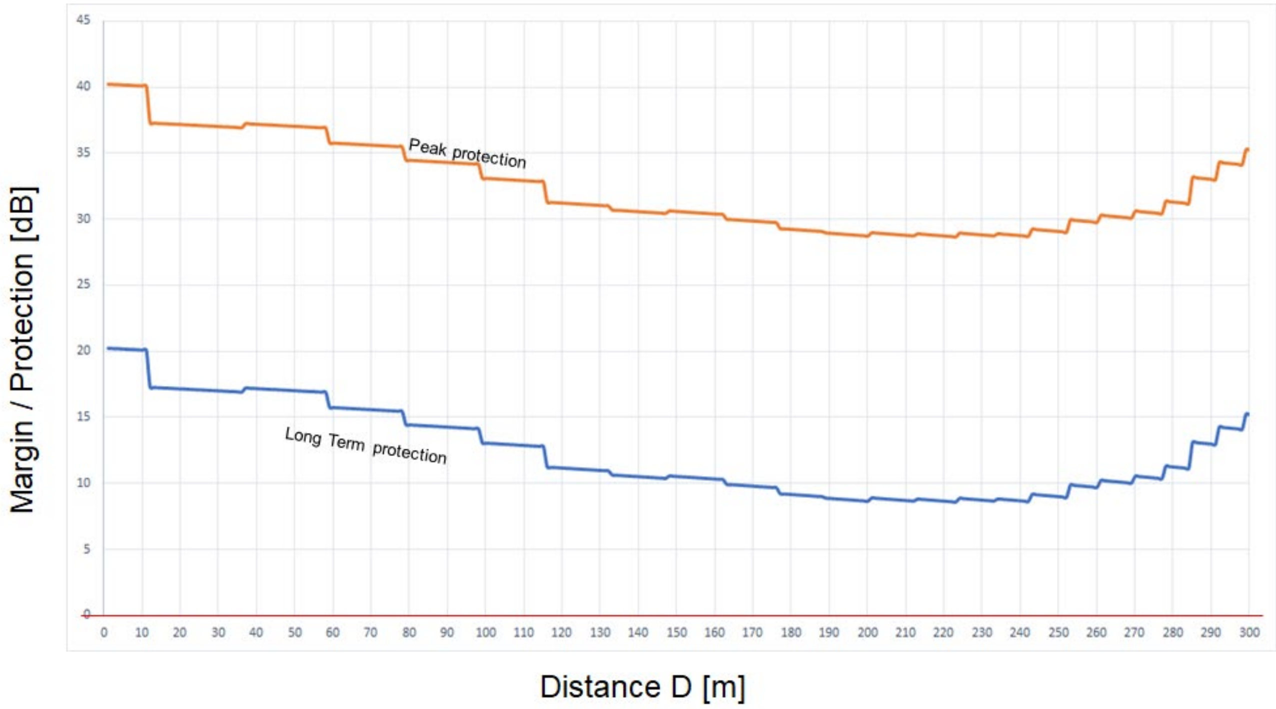


Figure 35: protection margin for FS scenario 3 in the adjacent case and a front radar with unwanted emissions of -33 dBm/MHz within the FS range

4.3.4 Summary single entry studies

Vehicular radar within the adjacent bands (either candidate band 1, adjacent to FS in 130-134.5 GHz, or candidate band 2, adjacent to FS in 141-148.5 GHz and FS in 130-134.5 GHz, (see Figure 2)):

Unwanted emissions (Spurious/OOB) level ≥ 130 GHz:

- must be ≤ -33 dBm/MHz e.i.r.p. (measured as a mean power density) for front radar;
- must be ≤ -36 dBm/MHz e.i.r.p (measured as a mean power density) for corner and short/ultra-short range.

Note: the difference between long-range and corner/short-range is based on the differences in the sidelobe antenna pattern and the interference scenario (misalignment).

Vehicular radar within candidate band 3 (in-band case, (see Figure 2)):

The maximum wanted emissions requirements within 141 GHz and 148.5 GHz for an automotive radar (all types) are:

- a maximum power spectral density (PSD) of -36 dBm/MHz e.i.r.p.;
- -6 dBm mean e.i.r.p. within 1 GHz;
- -1 dBm peak e.i.r.p. within 1 GHz.

These limits would allow sharing based on the single entry assessments.

4.4 RESULTS FOR IN-CABIN VEHICULAR RADARS

Similar to the assumptions for the interference scenarios made for exterior vehicular radars (see section 4.3), the assessment of interference between the in-cabin vehicular radars and fixed services was made. The main differences between the in-cabin and exterior vehicular radars are, apart from different RF maximum ratings (compare Table 7 vs. Table 14), the installation position of transceivers, thus different orientation towards the victim system, and the vehicle exit loss (see Table 9). Installation positions were assumed to be either under the roof of the vehicle or on the B-pillar, main antenna directivity pointing down the floor in different angles (see Figure 8 and Figure 38). The first scenario (see Figure 23) was assumed a worst-case scenario with highest interference potential between in-cabin radar and the victim system and was adopted regarding the source hight, sensor position in vehicle to the ground (see Figure 36).

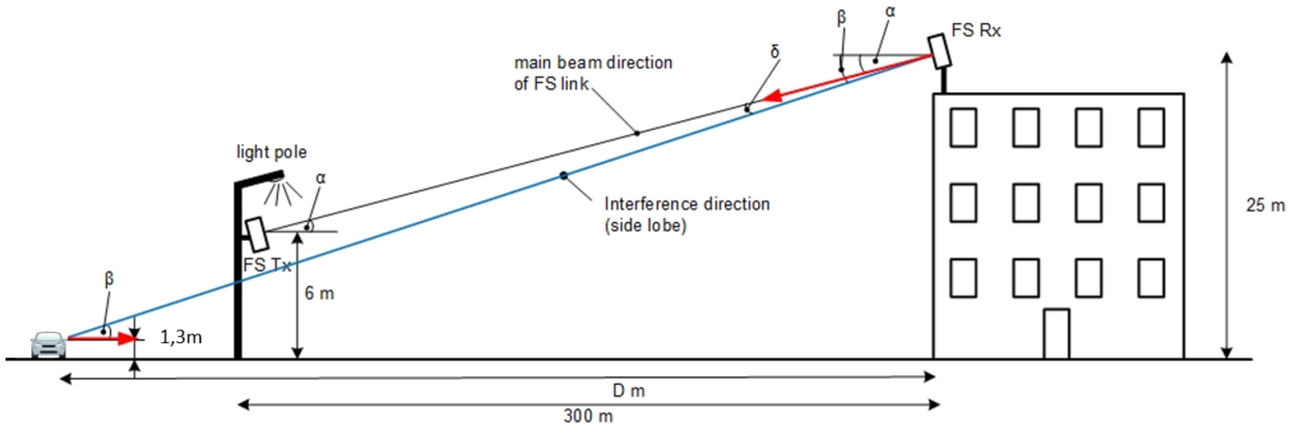


Figure 36: Light pole connected to a building adapted for in-cabin applications

4.4.1.1 Results single entry adjacent case

Given that the in-band studies for exterior radars indicate the scenario 1 as the most critical, the in-cabin interference was assessed first for this scenario as well. Then it was verified if the resulting power levels also protect FS in scenarios 2 and 3. Furthermore, the adjacent calculations into the 130-134.5 GHz band were assumed the worst case, since the emissions in higher frequency bands suffer higher free space losses as shown in Figure 37 (for detailed information, please see calculations added in ANNEX 3).

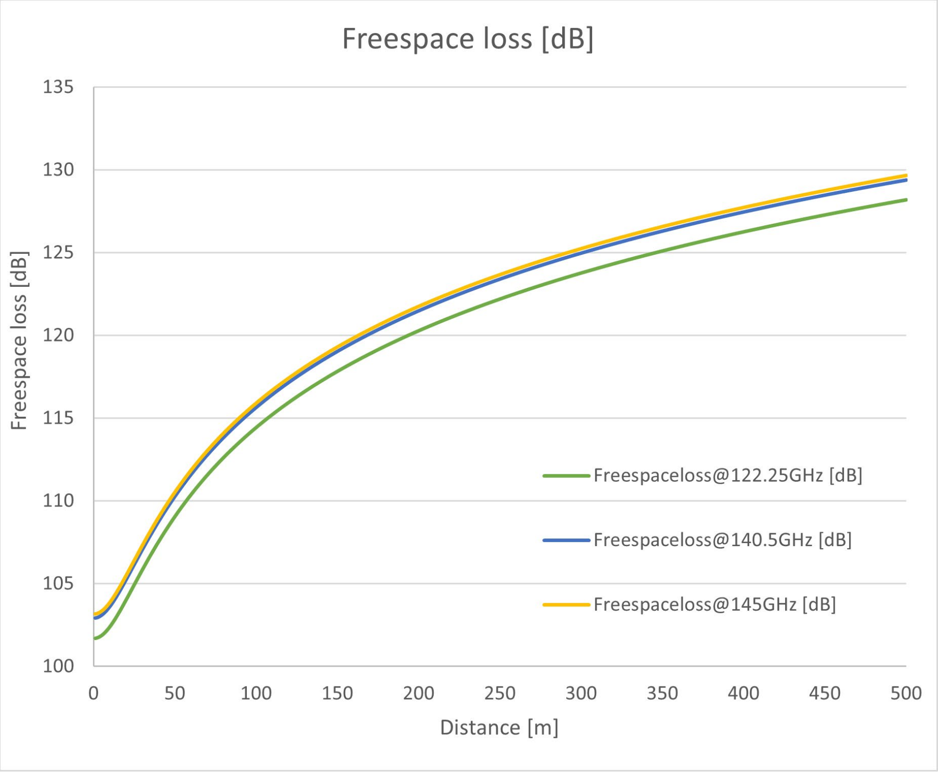


Figure 37: Free space loss @122GHz vs. Free space loss @140GHz and @145GHz

For the in-cabin calculations the following values were assumed:

- The limit within the FS range is minimum 20 dB below the mean power density limit in-band (OOB -20 dB)
- The maximum band width of the automotive radar was 14.5 GHz
- The antenna pattern of the automotive radar in the unwanted domain of the radar is similar to the in-band pattern (see Figure 39 and compare to Figure 9)

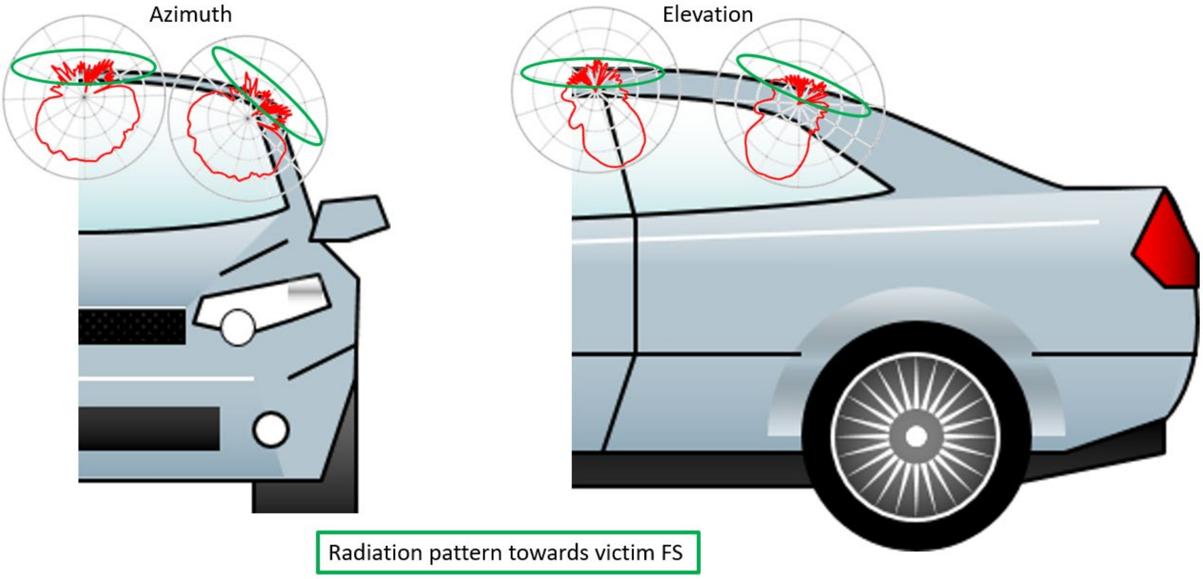


Figure 38: Orientation of the sensors in-cabin radars

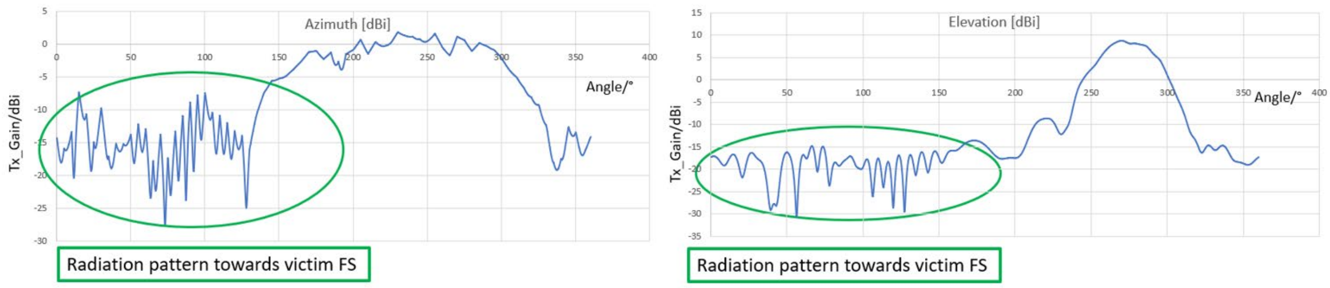


Figure 39: Antenna pattern incl. side and back lobes towards victim

The studies are based on the simulated in-vehicle radar antenna pattern shown in Figure 39. Due to the geometry of the interference scenario, the FS station will be interfered through the side lobes of the in-cabin radar, circled in Figure 39. The simulated radar antenna pattern does not represent all possible antennas, where the sidelobes can greatly vary from unit to unit and based on the used technology. Usually, single entry studies therefore consider the envelope of a large set of antennas. This has not been done here but the large margins that the studies resulted in suggest this would not change the conclusions, assuming the e.i.r.p. levels remain the same.

The results for the adjacent case into the 130-134.5GHz band for installation positions 1, 3 and 4, assuming position 2 equal to position 3 (see Figure 8), are shown in Figure 40-Figure 42.

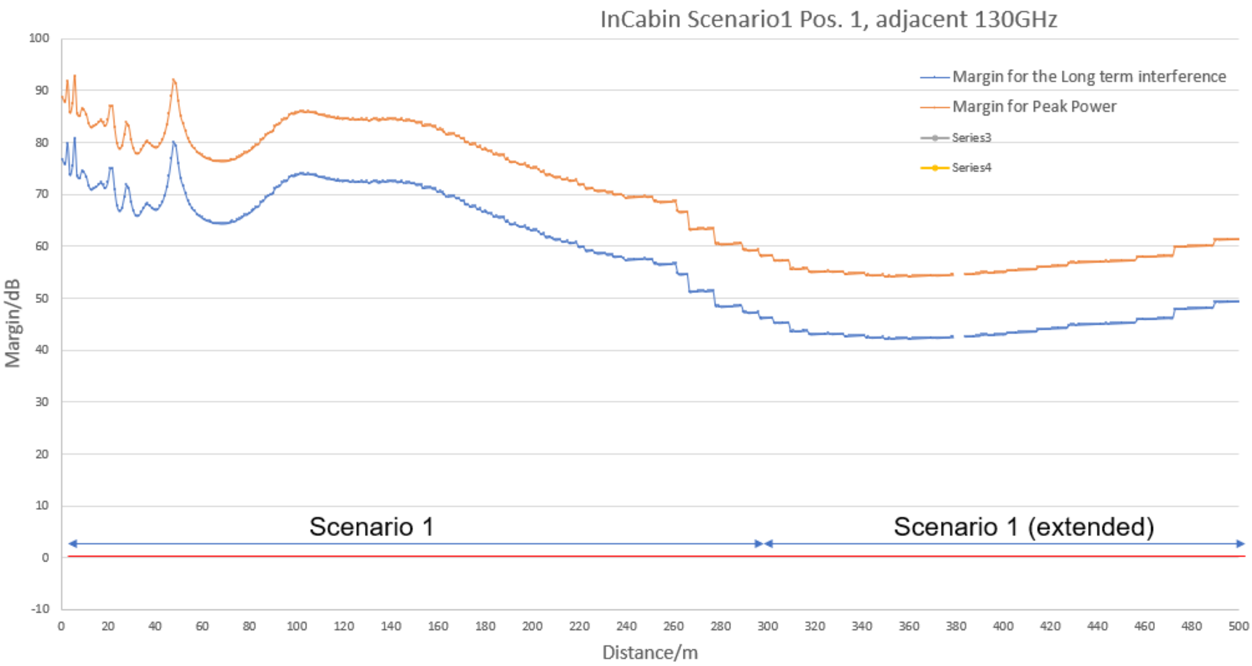


Figure 40: Results single entry adjacent case automotive in-cabin radar installation position 1

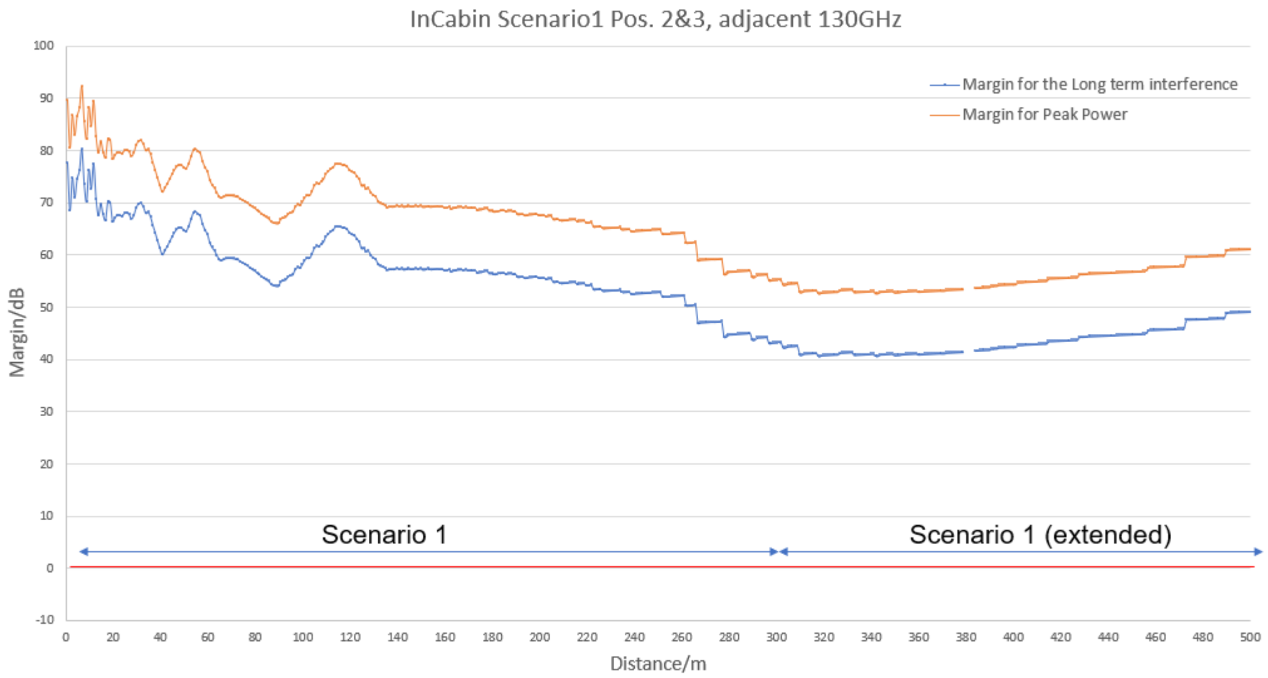


Figure 41: Results single entry adjacent case automotive in-cabin radar installation position 2 and3

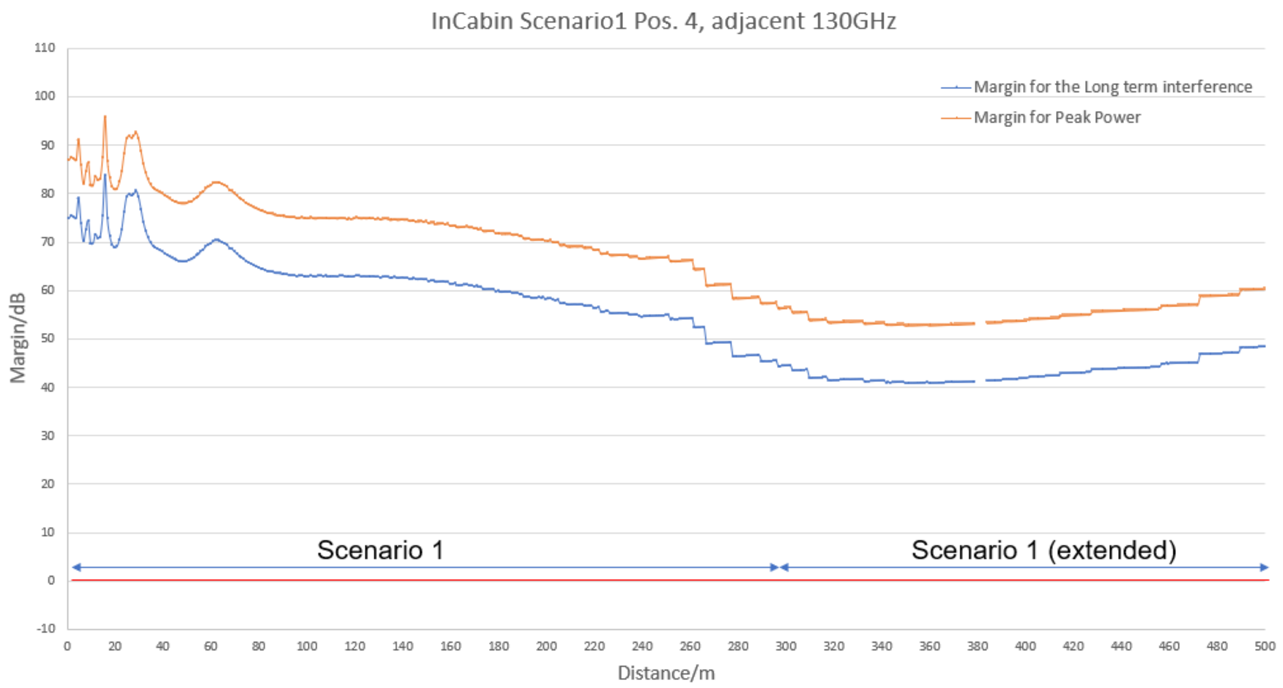


Figure 42: Results single entry adjacent case automotive in-cabin radar installation position 4

4.4.1.2 Results single entry in-band case

The results for the in-band case within 141-148.5 GHz band for installation positions 1, 3 and 4, assuming position 2 equal to position 3 (see Figure 8), are shown in Figure 43-Figure 45.

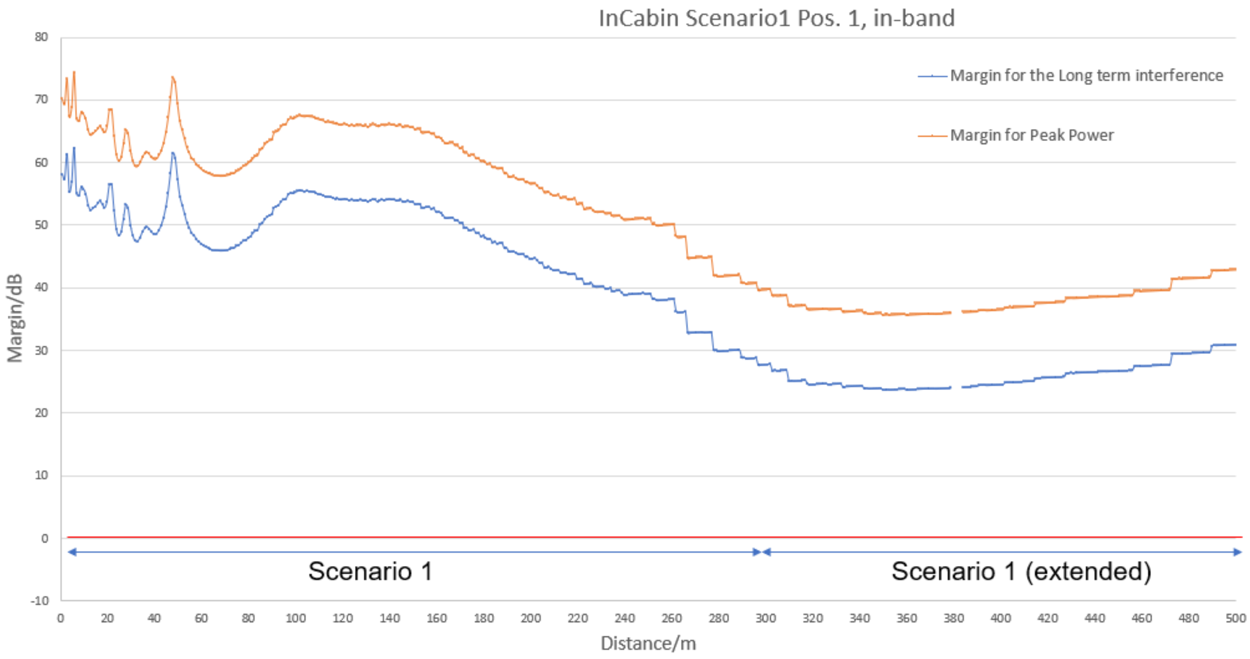


Figure 43: Results single entry in-band case automotive in-cabin radar installation position 1

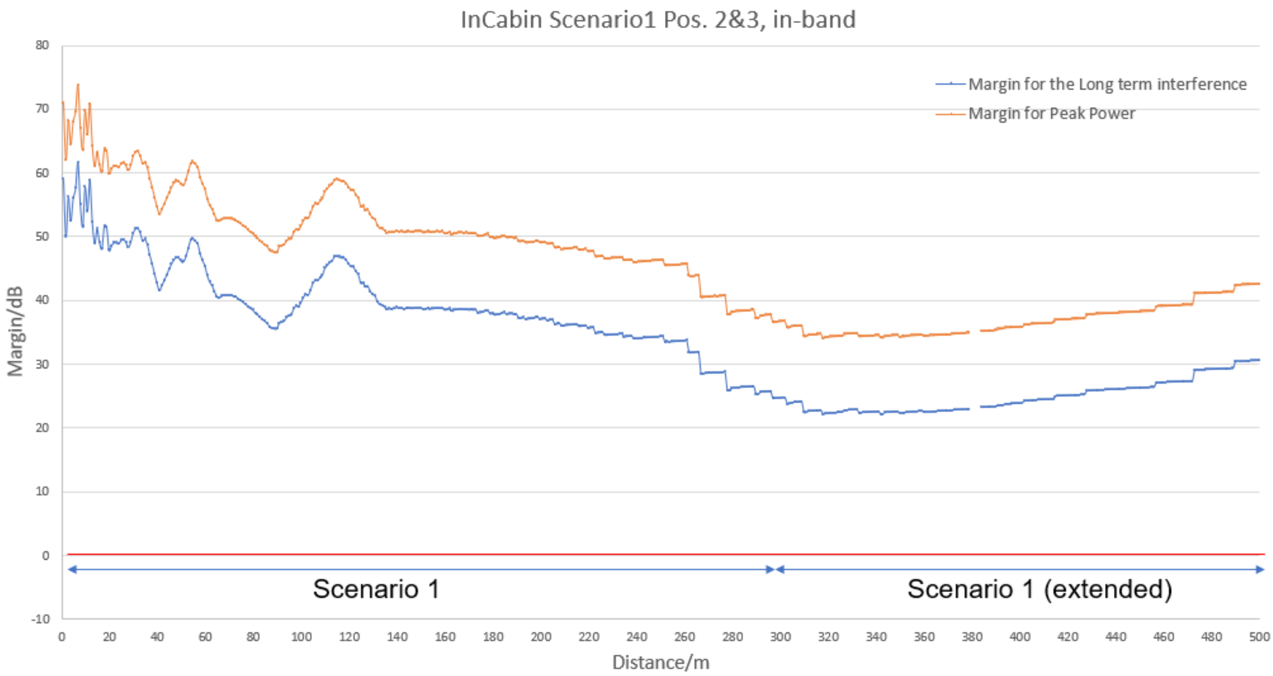


Figure 44: Results single entry in-band case automotive in-cabin radar installation position 2 and 3

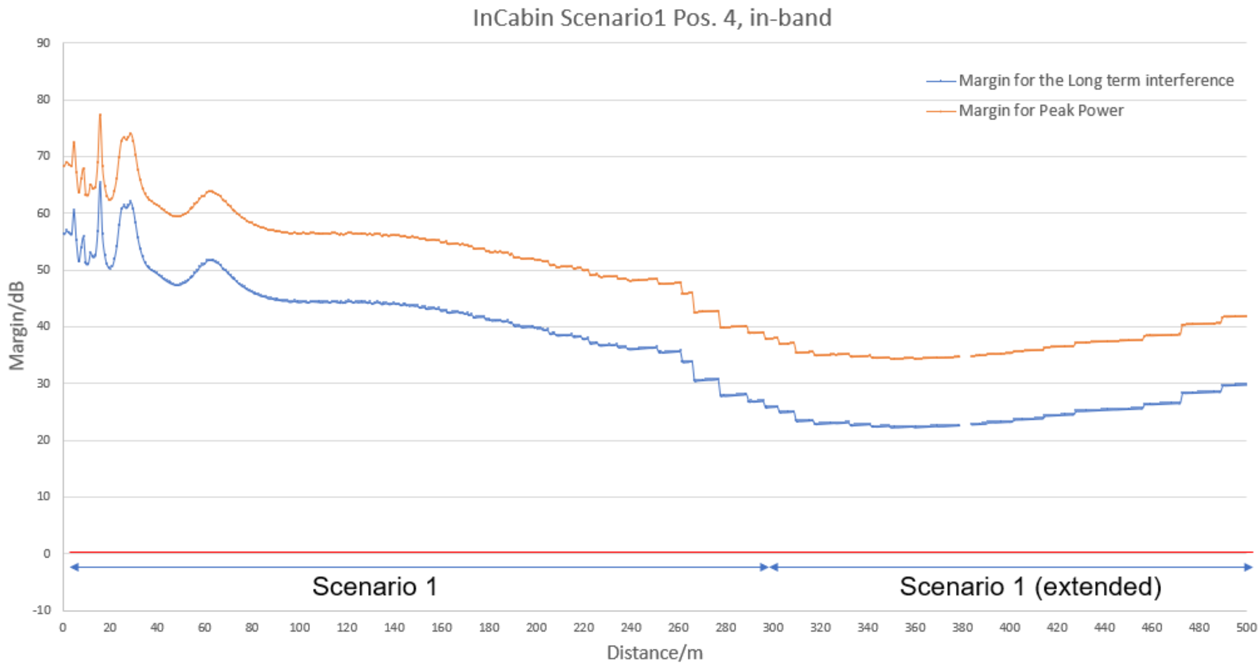


Figure 45: Results single entry in-band case automotive in-cabin radar installation position 4

4.4.1.3 Summary single entry studies in-cabin radar

The in-band calculations within 141-148.5 GHz band for installation positions 1, 3 and 4 and for the scenario 1, assumed as a worst-case scenario, show a minimal positive margin of 34.3 dB for peak power and 22.3 dB for long-term interference to the protection level within the frequency band. The adjacent case calculations for the worst-case scenario in single entry studies (scenario 1 for candidate band 1) show a minimal positive margin of 53 dB for peak power and 41 dB for long-term interference to the protection level within the adjacent frequency band. For all other studied adjacent cases (scenario 2 and 3 as well as adjacent to 141-148.5 GHz band), the minimal positive margin values for both, peak power and long-term interference to the protection level are higher, thus protecting undisturbed function for fixed services.

5 SHARING AND COMPATIBILITY STUDIES WITH EESS (PASSIVE) SERVICE

5.1 EESS TECHNICAL PARAMETERS AND PROTECTION CRITERIA

5.1.1 Earth Exploration Satellite Service (passive) technical parameters

Passive sensors are used in the remote sensing of the Earth and its atmosphere by Earth exploration and meteorological satellites in certain frequency bands allocated to the Earth exploration-satellite service (EESS) (passive). The data derived from these passive sensor operations are used extensively in meteorology, climatology, and other disciplines for operational and scientific purposes. These sensors are sensitive to in-band emissions. Therefore, RF emissions above a certain level may constitute interference to the passive sensors using the same frequency bands. This is mainly due to the fact that passive sensors may not be able to differentiate the wanted signal from the interference and that interference may not be identifiable in the passive sensor output data (see Recommendation ITU-R RS.1861 [13]).

Typical technical and operational characteristics of Earth Exploration-Satellite Service (passive) systems using allocations between 1.4 and 275 GHz for utilization in sharing studies can be found in Recommendation ITU-R RS.1861 [13]. The frequency bands and bandwidths used for satellite passive remote sensing with information on specific measurements conducted in these frequency bands (meteorology-climatology, chemistry) can be furthermore extracted from Recommendation ITU-R RS.515-5 [14].

Recommendation ITU-R RS.1861, sections 6.14 and 6.15, are relevant to this ECC Report.

Table 20 and Table 21 provide the technical and operational characteristics for the various EESS (passive) bands between 114.25 and 151.5 GHz. The corresponding EESS (passive) sensors are either taken from ITU-R Recommendation RS.1861 or from ESA/EUMETSAT existing or planned sensors.

Table 20: Passive sensor parameters in the 114.25 to 122.25 GHz band

EESS sensor	MWI	Planned EUMETSAT radiometer (ECC Report 190 [28])
Type of sensor	Conical Scan	Conical Scan
Orbit altitude (km)	830	800
Nadir angle (°)	45.2	45.2
Slant path distance (km)	1269	1219
Free space loss (dB)	195.7	195.3
Elevation angle at ground (°)	36.7	37.0
Attenuation due to atmospheric gases (dB)	3.2	3.2
Reference bandwidth (MHz)	200	200
EESS protection criterion (dBW/reference bandwidth)	-166	-166
Apportionment factor (dB)	12	12
EESS protection criterion (with relevant apportionment) (dBW/reference bandwidth)	-178	-178
EESS sensor antenna gain (dBi)	55.5	55
EESS footprint size (km²)	82	82

Table 21: Passive sensor parameters in the 148.5 to 151.5 GHz band

EESS sensor	System N1 (Nadir)	System N1 (Outer)
Type of sensor	Nadir Scan	Nadir Scan
Orbit altitude (km)	705	705
Nadir angle (°)	0	48.95
Slant path distance (km)	705	1166
Free space loss (dB)	192.8	197.2
Elevation angle at ground (°)	90.0	33.1
Attenuation due to atmospheric gases (dB)	2	3.8
Reference bandwidth (MHz)	500	500
EESS protection criterion (dBW/reference bandwidth)	-159	-159
Apportionment factor (dB) (Note 1)	12	12
EESS protection criterion (with relevant apportionment) (dBW/reference bandwidth)	-171	-171
EESS sensor antenna gain (dBi)	45	45
EESS footprint size (km²)	154	759
Note 1: In accordance with ECC Report 334, section 3.5.4.3 [7], a 12 dB apportionment factor has been consistently used for the analysis related to EESS (passive).		

5.1.2 EESS protection criteria

Information on the performance and interference criteria for satellite passive remote sensing of the Earth and its atmosphere for microwave passive sensors can be found in Recommendation ITU-R RS.2017-0 [15]. An extract from this Recommendation dealing with interference criteria for the frequency range from 114.25 to 151.5 GHz is shown in Table 22.

Table 22: Interference criteria for satellite passive remote sensing in the frequency range 114.25-151.5 GHz (extract from Recommendation ITU-R RS.2017-0, table 2)

Frequency band(s) (GHz)	Reference bandwidth (MHz) (Note 3)	Maximum interference level (dBW) (Note 3)	Percentage of area or time permissible interference level may be exceeded (%) (Note 1)	Scan mode (Note 2)
114.25-116	10	-189	1	L
115.25-122.25	200/10	-166/-189	0.01/1	N, L
148.5-151.5	500/10	-159/-189	0.01/1	N, L

Note 1: For a 0.01 % level, the measurement area is a square on the Earth of 2000000 km², unless otherwise justified; for a 0.1 % level, the measurement area is a square on the Earth of 10000000 km² unless otherwise justified; for a 1 % level, the measurement time is 24 h, unless otherwise justified.
Note 2: N: Nadir, Nadir scan modes concentrate on sounding or viewing the Earth's surface at angles of nearly perpendicular incidence. The scan terminates at the surface or at various levels in the atmosphere according to the weighting functions. L: Limb, Limb scan modes view the atmosphere "on edge" and terminate in space rather than at the surface, and accordingly are weighted zero at the surface and maximum at the tangent point height. C: Conical, Conical scan modes view the Earth's surface by rotating the antenna at an offset angle from the nadir direction.
Note 3: First number for nadir or conical scanning modes and second number for microwave limb sounding applications.

5.2 INTERFERENCE SCENARIOS

5.2.1 Aggregation

At a given time, interference to EESS (passive) is produced by all radio transmitters present in the sensor footprint (IFOV). The size of the footprint mainly depends on the orbit height, nadir angle and antenna 3 dB beamwidth, and can be in the range of several tens to several hundreds of km² (see ECC Report 334 [7] section 3.5.4.1). The aggregation from all transmitters in the EESS (passive) footprint is assessed, as defined in Table 23.

Table 23: Aggregation parameters

Application	Passive sensors (satellite)	bands under RR N°5.340	bands under RR N°5.340
Frequency band (GHz)	116-122.25	148.5-151.5	148.5-151.5
EESS sensor	MWI	System N1 (Nadir)	System N1 (Outer)
EESS footprint size (km²)	82	154	759
Number of vehicles in footprint (urban/suburban)	27060	50820	250470
Number of vehicles in footprint (highway)	10086	18942	93357

5.2.2 Methodology

For Nadir and Conical scan EESS (passive) sensors, the maximum emissions levels on the ground from a population of UWB radars operated within the EESS (passive) footprint area are calculated as follows:

$$\boldsymbol{E_{max} = I_{max} - G_{max} + L_{Atmos} + L_{FS}} \qquad (3)$$

Where:

- E_{max} – max. emission level on Earth's surface in the direction towards the satellite (in dBW in the reference bandwidth);
- I_{max} – EESS (passive) protection criteria (with appropriate apportionment, in dBW in the reference bandwidth);
- G_{max} – EESS (passive) maximum antenna gain (in dBi);
- L_{Atmos} – Atmospheric losses (at relevant elevation, in dB);
- L_{FS}– Free space loss (along the slant path D, in dB).

The Earth-satellite geometry to be considered for the case of Nadir and Conical scanning instruments is described in Figure 46.

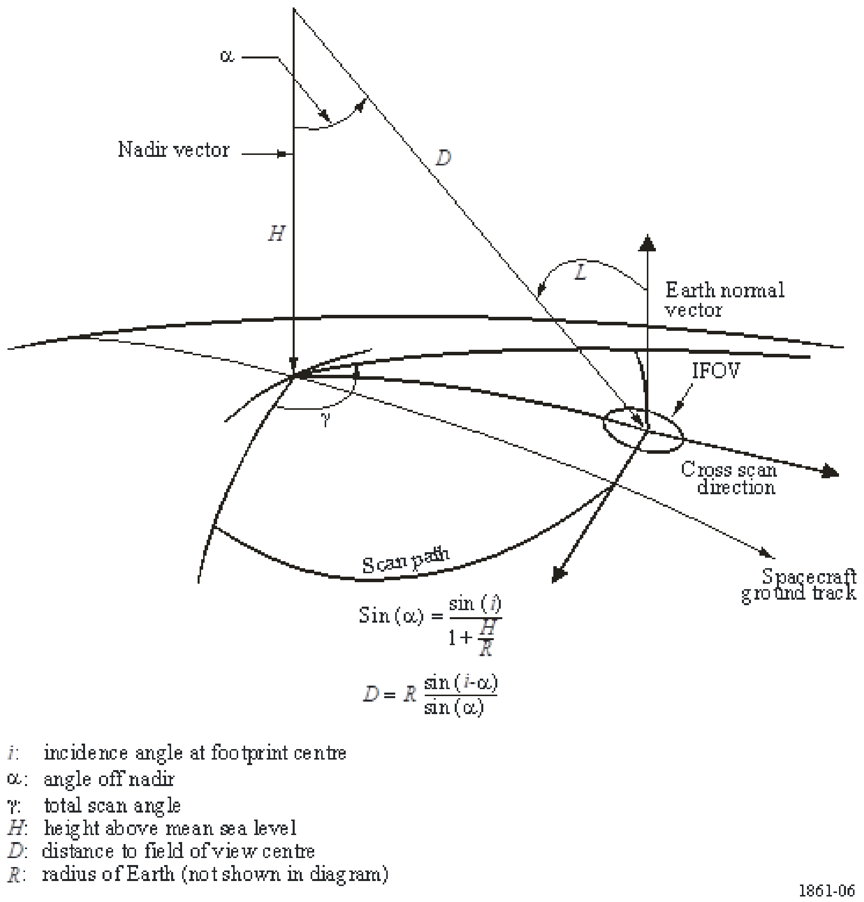


Figure 46: Earth-satellite geometry for the nadir and conical scanning EESS (passive) sensors

5.2.3 Interference scenarios for exterior vehicular radar

As described in section 2.1.2, three potential frequency bands have been defined for exterior vehicular radar:

- candidate band 1: 122.25 to 130 GHz;
- candidate band 2: 134 to 141 GHz;
- candidate band 3: 141 to 148.5 GHz.

These three potential bands affect allocations for EESS, which are located adjacent to these bands, and are in operation in the band 114.25 to 122.25 GHz, or in the band 148.5 to 151.5 GHz.

These three bands have been investigated in aggregate studies for the two different vehicle density cases "urban/suburban" and "highway". For the urban/suburban case a density of 330 vehicles/km² and for the highway case a density of 123 vehicles/km² have been assumed, respectively.

In these studies, the individual residual margin (see section 3.4.4 in [7]) to the interference criterion is determined by means of the technical parameters (see section 2.1.3), the antenna data (see section 2.1.3.1), the defined interference scenarios (see section 5.2.3) and the protection requirements for EESS (see section 5.1.2). The exact calculations can be found in an Excel-spreadsheet which is attached to this Report.

As illustrated in Figure 47, compatibility assessment between exterior vehicular radar (EVR) and EESS or bands under RR No. 5.340 was performed for the following configurations:

- EVR in the band 122.25 to 130 GHz and EESS (passive) in the band 114.25 to 122.25 GHz (yellow arrow in Figure 47);
- EVR in the band 141 to 148.5 GHz and EESS (passive) and bands under RR N°5.340 in the band 148.5 to 151.5 GHz (green arrow in Figure 47).

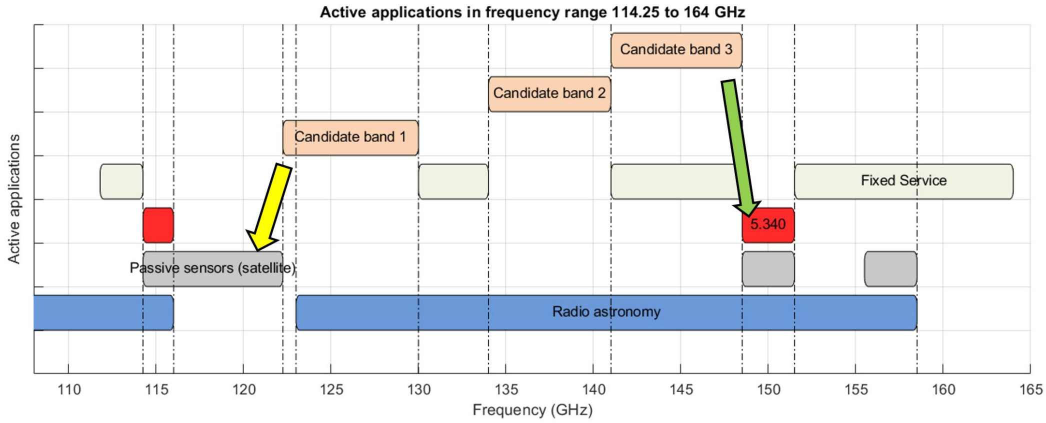


Figure 47: 110-160 GHz spectrum: compatibility study between EVR and EESS bands and bands under RR No.5.340

For the interference scenarios where the victim EESS is at 90° (nadir) direction, thus above the EESS footprint on the ground, two component paths have been assumed for each radar: one direct LOS component and one reflected component:

- For the direct LOS component, 90° attenuation antenna off-pointing gain is assumed;
- For the reflected component, 30 dB attenuation from peak power is assumed.

This is illustrated by Figure 48(a).

For the interference scenarios where the victim EESS is at mid-elevation direction, thus not above the EESS footprint on the ground, three component paths have been assumed: one direct LOS component for radars facing the victim EESS, one direct LOS component for radars facing opposite direction and reflected component.

- For the direct LOS component for radars facing the victim EESS (assuming half of radars of a given type), 45° attenuation antenna off-pointing gain is assumed.
- For the direct LOS component for radars facing opposite direction (assuming half of radars of a given type), 90° attenuation antenna off-pointing gain is assumed.
- For the reflected component, 30 dB attenuation from peak power is assumed.

This is illustrated in Figure 48(b).

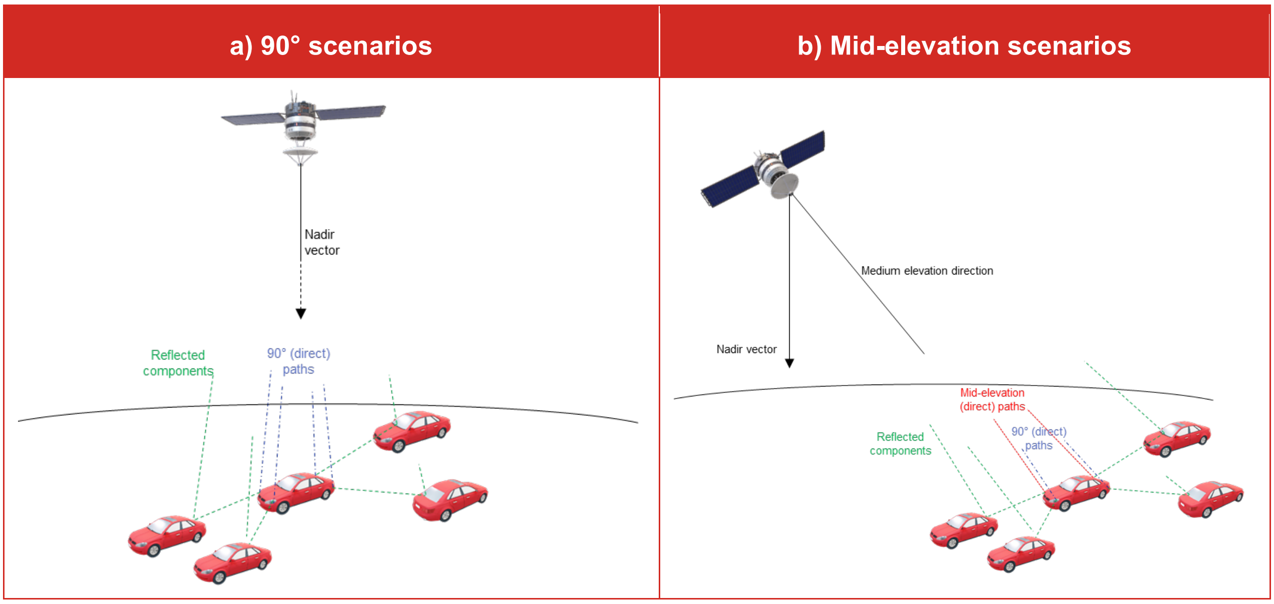


Figure 48: Illustration of EESS scenarios, with direct LOS paths and indirect paths (reflected component)

5.2.4 Interference scenarios for in-cabin vehicular radar

The considered frequencies for the in-cabin vehicular radar are:

- 116-130 GHz;
- 134-141 GHz;
- 141-148.5 GHz.

In sharing and compatibility studies for in-cabin radar with EESS, following satellite systems are considered:

Satellites 116-122.25 GHz (in-band):

- MWI, elevation angle at the ground 36.7°;
- Planned EUMETSAT, elevation angle at the ground 37°.

Satellites 116-122.25 GHz (adjacent band):

- MWI, elevation angle at the ground 36.7°;
- Planned EUMETSAT, elevation angle at the ground 37°.

Satellites 148.5-151 GHz (adjacent band):

- System N1 (Nadir), elevation at ground 90°;
- System N1 (Outer), elevation at ground 33.1°.

For completeness of the interference studies also frequency band 122.25-130 GHz is considered. In this case the frequency band 114.25-122.25 GHz is considered as adjacent band.

Figure 49 illustrates scenarios for in-cabin radar for various mounting positions of the sensor and relevant EESS systems: System N1, MWI and EUMETSAT. The blue, red and green lines indicate the angle for each of the systems.

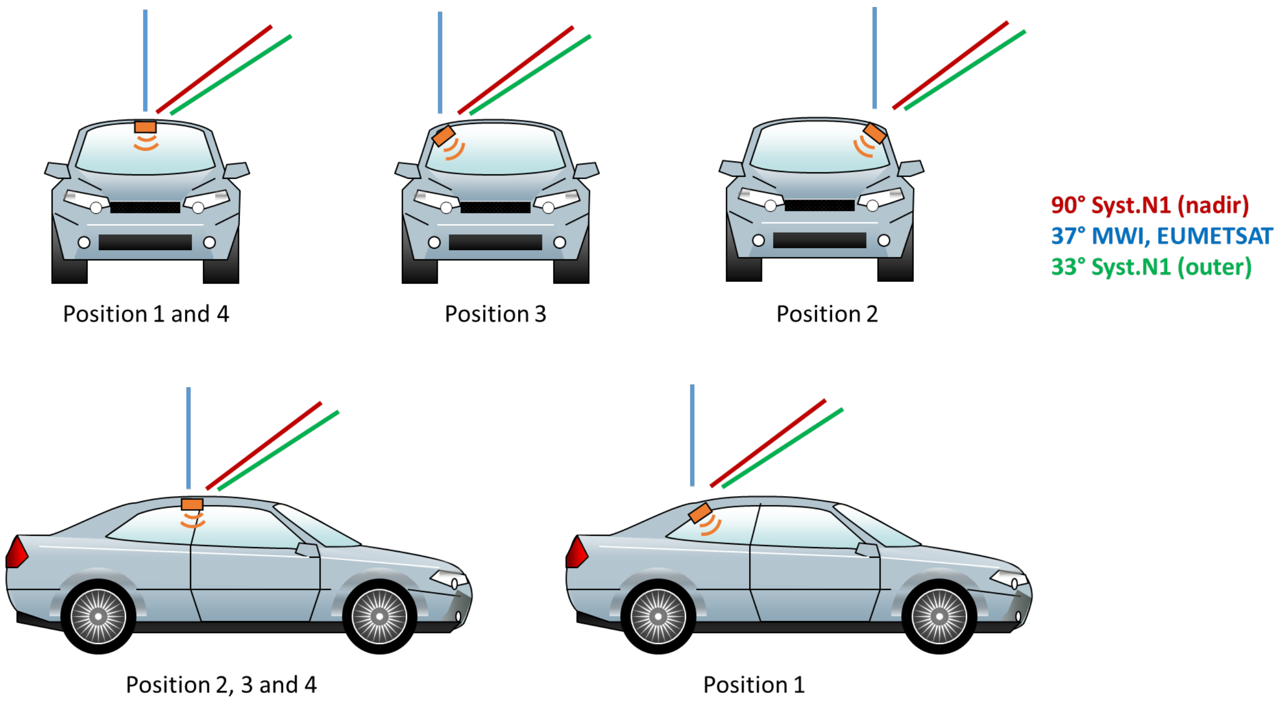


Figure 49: Scenarios for in-cabin radar for various mounting positions and EESS systems

The car exit loss for single entry study and aggregated studies was estimated out of measurement data with conventional car and car with sunroof. Table 24 summarises the values for car exit loss for cases considered in compatibility study.

Table 24: Car exit loss for compatibility study in-cabin radar with EESS

Incidence angle	90°	35°
Satellite	System N1 (Nadir)	MWI, EUMETSAT, System N1
Single entry study	27 dB	15 dB
Aggregated study	33 dB	27 dB

5.3 RESULTS FOR EXTERIOR VEHICULAR RADAR

5.3.1 Presentation of the results

The exterior vehicular radar technical parameters described in section 2.1.3 and the antenna characteristics described in section 2.1.3.1 have been used for studies at different frequencies and configurations The results are summarised in the below tables. A positive margin indicates that the interference criterion is fulfilled and a negative margin that the criterion is violated. Detailed computations are visible in an attached Excel calculator.

Table 25 shows the aggregate worst-case results for exterior vehicular radars for:

- EVR frequency range: 122.25 to 130 GHz;
- EESS band: 116 to 122.25 GHz;
- Evaluated EESS frequency: 119.125 GHz (OOB);
- EESS victim sensor: MWI.

Table 25: Margins to the EESS interference criterion determined in an aggregate study for EVR in the urban/suburban scenario, for EESS frequency 119.125 GHz, MWI

EVR type	Margin to interference criterion (Urban/suburban)	Margin to interference criterion (Highway)
Short/ultra-short	+3.8 dB	+8.1 dB
Corner	+5 dB	+9.8 dB
Front	+10.0 dB	+14.3 dB
Short/ultra-short + corner	+1.6 dB	+5.8 dB
Short/ultra-short + corner+ front	+1 dB	+5.3 dB

Table 26 shows the aggregate worst-case results for short-range assist for:
- EVR frequency range: 141 to 148.5 GHz;
- EESS band: 148.5 to 151.5 GHz;
- Evaluated EESS frequency: 150 GHz (OOB);
- EESS victim sensor: System N1 (Nadir).

Table 26: Margins to the EESS interference criterion determined in an aggregate study for EVR in the urban/suburban scenario, for EESS frequency 150 GHz, System N1 (Nadir)

EVR type	Margin to interference criterion (Urban/suburban)	Margin to interference criterion (Highway)
Short/ultra-short	+12.3 dB	+16.6 dB
Corner	+14.1 dB	+18.4 dB
Front	+18.9 dB	+23.1 dB
Short/ultra-short + corner	+10.1 dB	+14.4 dB
Short/ultra-short + corner+ front	+9.6 dB	+13.8 dB

Table 27 shows the aggregate worst-case results for short-range assist for:
- EVR frequency range: 141 to 148.5 GHz;
- EESS band: 148.5 to 151.5 GHz;
- Evaluated EESS frequency: 150 GHz (OOB);
- EESS victim sensor: System N1 (outer).

Table 27: Margins to the EESS interference criterion determined in an aggregate study for EVR in the urban/suburban scenario, for EESS frequency 150 GHz, System N1 (Outer)

EVR type	Margin to interference criterion (Urban/suburban)	Margin to interference criterion (Highway)
Short/ultra-short	+9.7 dB	+14.0 dB
Corner	+11.5 dB	+15.8 dB
Front	+16.0 dB	+20.3 dB
Short/ultra-short + corner	+7.5 dB	+11.8 dB
Short/ultra-short + corner+ front	+6.9 dB	+11.2 dB

5.3.2 Conclusions

From the results presented in above Table 25, Table 26 and Table 27, it can be observed that urban/suburban scenarios (in the middle column) are more challenging (yielding a lower margin to the EESS interference criterion) than the highway scenarios (in the rightmost column), with an offset between those of approximately 4.3 dB. Therefore, the urban/suburban scenarios values (in the second column) can be concluded as the most relevant ones for this Report.

It can also be seen that ensuring protection of the EESS band 116 to 122.25 GHz (Table 25) is more challenging (yielding a lower margin to the EESS interference criterion) than the EESS band 148.5 to 151.5 GHz (Table 26 and Table 27).

All the results presented in the results presented in above Table 25, Table 26 and Table 27 exhibit positive margin to the EESS interference criterion, therefore it is concluded that compatibility between exterior vehicular radars and EESS bands or bands under RR No. 5.340 can be achieved, for all types of exterior vehicular radars (short/ultra-short, corner, front radars and all of them aggregated), for the set of parameters considered in the present Report.

5.3.3 Observations and discussion

5.3.3.1 Mid-elevation vs nadir scenarios

The Excel calculator can also be modified to find out the protection level towards adjacent EESS bands for which the results indicate zero margin. For the aggregate case of short/ultra-short + corner + front radars, the results are provided in Table 28.

Table 28: Minimum protection level needed towards adjacent EESS bands

EESS sensor and EESS band	MWI (mid-elevation) 116-122.25 GHz	System N1 (Nadir) 141-148.5 GHz	System N1 (Outer, Mid-elevation) 141-148.5 GHz
Minimum protection level needed to ensure >0 margin in adjacent EESS bands	-49 dBm/MHz	-40.5 dBm/MHz	-43.5 dBm/MHz

It can also be seen from Table 28 that the most challenging (lower minimum protection level needed) system to protect is MWI (which is mid-elevation) in the 116-122.25 GHz band with -49 dBm/MHz protection limit. Then, in the 141-148.5 GHz band, comes protection of system N1 outer (which is also mid-elevation) with -43.5 dBm/MHz, whereas the protection of system N1 Nadir is less challenging with -40.5 dBm/MHz.

Thus, we conclude that protecting mid-elevation cases is the most challenging scenario. Very likely, if mid-elevation systems are protected (MWI and N1 outer), nadir (N1 nadir) ones would also be protected.

5.3.3.2 Front and corner-short radars contribution comparison

The compatibility assessment that is carried out by the calculator can be expressed by the equation (1), for compatibility with mid-elevation systems, respectively. This equation defines that the aggregation of all radar signals should not exceed a maximum interference level.

$$\sum_{k=1}^{k=N_{radar}} OOBE_k * DC_k * (0.5 * AOPmid_k + 0.5 * AOPnad_k + ScatGain) \leq OOBE_{\max} \quad (4)$$

Where:

- N_{radar} is the number of radars (e.g. 1+4+6=11);
- $OOBE_k$ is the protection level in EESS adjacent bands, by radar k (e.g. -50 dBm/MHz);

- DC_k is the duty cycle of radar k (e.g. 25% or 50%);
- $AOPmid_k$ is the mid-elevation antenna off-pointing gain of radar k;
- $AOPnad_k$ is the nadir antenna off-pointing gain of radar k;
- $ScatGain$ is the Scattering coefficient of the reflected component (e.g. -30 dB);
- $OOBE_{\max}$ is the emission limit dBm/MHz.

In order to compare the contribution of different radar types, the product of several factors within the sum if equation (4) can be evaluated, as shown by equations (5) and (6).

$$contribution_{shortradar} = DC_{short} * (0.5 * AOPmid_{short} + 0.5 * AOPnad_{short} + ScatGain) \quad (5a)$$
$$contribution_{shortradar} = 0.25 * (0.5 * -24.2dB + 0.5 * -28.7dB - 30dB) = -30.5dB \quad (5b)$$
(5)

$$contribution_{frontradar} = DC_{front} * \left(0.5 * AOPmid_{front} + 0.5 * AOPnad_{front} + ScatGain\right) \quad (6a)$$
$$contribution_{frontradar} = 0.5 * (0.5 * -28.1dB + 0.5 * -32.6dB - 30dB) = -29.9dB \quad (6b)$$
(6)

Comparing equations (5b) and (6b), it can also be observed that the contribution of front or corner/short radars is actually quite similar, despite some difference in parameters. The reason is that while front radars have twice the duty cycle of short/corner radars (50% vs 25%), the difference in antenna off-pointing (due to more directive antenna pattern) balances out the duty cycle by approximately the same amount.

Therefore, elaboration of a set of requirements per radar, without distinction of radar types appears as a viable option.

5.3.4 Proposal set of requirements to ensure compatibility with EESS systems

The following technical requirements on radars' unwanted emissions towards the EESS bands, in terms of maximum transmit power in the unwanted emissions domain and antenna directivity would ensure compatibility with EESS in the adjacent bands.

For radars operating in the 122.25-130 GHz band:

- For radars with maximum duty cycle $DC_{max} \leq 50\%$:
  - Maximum (mean) e.i.r.p. density in band 116-122.25 GHz: -50 dBm/MHz;
  - Maximum (mean) e.i.r.p. density above 35° elevation in band 116-122.25 GHz: -76 dBm/MHz.
- For radars with maximum duty cycle $DC_{max} > 50\%$:
  - Maximum (mean) e.i.r.p. density in band 116-122.25 GHz: -53 dBm/MHz;
  - Maximum (mean) e.i.r.p. density above 35° elevation in band 116-122.25 GHz: -79 dBm/MHz.

For radars operating in the 134-148.5 GHz band:

- For radars with maximum duty cycle $DC_{max} \leq 50\%;$
  - Maximum (mean) e.i.r.p. density in band 148.5-151 GHz: -44 dBm/MHz;
  - Maximum (mean) e.i.r.p. density above 35° elevation in band 148.5-151 GHz: -70 dBm/MHz.
- For radars with maximum duty cycle $DC_{max} > 50\%;$
  - Maximum (mean) e.i.r.p. density in band 148.5-151 GHz: -47 dBm/MHz;
  - Maximum (mean) e.i.r.p. density above 35° elevation in band 148.5-151 GHz: -73 dBm/MHz.

5.4 RESULTS FOR IN-CABIN VEHICULAR RADAR

The main technical parameters of in-cabin vehicular radar are described in section 2.2.3. Considered interference scenarios are described in section 5.2.4. The following tables summarise results of the interference study. A positive margin indicates that the interference criterion for this configuration is fulfilled. Negative margin indicates that the criterion is violated. Detailed calculations are included in an Excel sheet attached to this Report.

5.4.1 Results of studies

Three interference scenarios were considered in the studies:

5.4.1.1 Scenario 1: Radars and satellites operate in the same band (in-band sharing)

Table 29 shows the single entry and aggregated results for:

- In-cabin radar operating co-frequency with EESS (passive) within 116-122.25 GHz band;
- EESS (passive) victims: MWI and planned EUMETSAT system, operating in frequency band: 114.25 - 122.25 GHz;
- Evaluated EESS (passive) frequency: 116.125 GHz.

The in-cabin sensor is in-band with EESS (passive).

Table 29: Margins for the EESS (passive) interference criterion determined for in-cabin radar working in 116-122.25 GHz frequency band (co-frequency scenario)

EESS	Margin to interference criterion for single entry	Margin to interference criterion for aggregated study
MWI	20.36 dB	-14.98 dB
EUMETSAT	20.51 dB	-14.82 dB

5.4.1.2 Scenario 2: Radars and satellites operate in the adjacent bands (Out of band compatibility)

Table 30 shows the single entry and aggregated results for:

- In-cabin radar operating within 122.25-130 GHz band, adjacent band with EESS (passive);
- EESS (passive) victims: MWI and planned EUMETSAT system, operating in frequency band 114.25-122.25 GHz;
- Evaluated EESS (passive) frequency: 116.125 GHz.

The in-cabin sensor is out-of-band with EESS (passive).

Table 30: Margins for the EESS (passive) interference criterion determined for in-cabin radar working in 122.25-130 GHz frequency band (adjacent band scenario)

EESS	Margin to interference criterion for single entry	Margin to interference criterion for aggregated study
MWI	40.36 dB	5.02 dB
EUMETSAT	40.51 dB	5.18 dB

5.4.1.3 Scenario 3: Radars and satellites operate in the adjacent bands (Out of band compatibility)

Table 31 shows single entry and aggregated results for:

- In-cabin radar operating within 141-148.5 GHz band, adjacent band with EESS (passive);
- EESS (passive) victims: System N1 (Nadir) and SystemN1 (Outer), operating in the frequency band 148.5-151.5 GHz;
- Evaluated EESS (passive) frequency: 150 GHz.

The in-cabin sensor is out-of-band with EESS.

Table 31: Margins for the EESS interference criterion determined for in-cabin radar working in 141-148.5 GHz frequency band (adjacent band scenario)

EESS	Margin to interference criterion for single entry	Margin to interference criterion for aggregated study
SystemN1 (Nadir)	61.85 dB	17.78 dB
System N1 (Outer)	56.02 dB	11.03 dB

5.4.2 Conclusions

Results of the studies given above show that, for both single entry and aggregated interference scenarios, the protection of the EESS (passive) would be ensured for in-cabin radar operating in the adjacent frequency bands 122.25-130 GHz and 141-148.5 GHz. On the other hand, the case of the protection of the EESS (passive) from in-cabin radar operating co-frequency in the frequency band 116-130 GHz depicts large negative margins for aggregated study for the band 116-122.25 GHz.

No mitigation technique has been determined that could be considered to ensure the protection of EESS from the aggregated effect of in-cabin radar in the 116-122.25 GHz band. Therefore the coexistence cannot be ensured with in-cabin radars.

For in-cabin radar working in frequency bands 122.25–130 GHz and 134-148.5 GHz, the following technical conditions could apply (on per radar basis).

Band 122.25-130 GHz:

- Maximum (mean) e.i.r.p. density in adjacent (EESS) band 116-122.25 GHz: -45 dBm/MHz;
- Downwards antenna orientation;
- Report shows that sensors integrated in conventional cars or cars with sunroof ensure at least 15 dB of exit-loss (attenuation) from the radar main beam to the EESS (passive) sensors' directions. In other cases, e.g. convertible cars, the minimum of 15 dB exit-loss (in worst case) needs to be proven. Process of proving is to be specified and agreed.

Band 134–148.5 GHz:

- Maximum (mean) e.i.r.p. density in adjacent (EESS) band 148.5-151 GHz: -39 dBm/MHz;
- Downwards antenna orientation;
- Report shows that sensors integrated in conventional cars or cars with sunroof ensure at least 15 dB of exit-loss (attenuation) from the radar main beam to the EESS (passive) sensors' directions. In other cases, e.g. convertible cars, the minimum of 15 dB exit-loss (in worst case) needs to be proven. Process of proving is to be specified and agreed.

6 SHARING AND COMPATIBILITY STUDIES WITH AMATEUR AND AMATEUR-SATELLITE SERVICES

6.1 SHARING WITH AMATEUR AND AMATEUR-SATELLITE SERVICES

The Amateur and Amateur-Satellite Services have secondary and primary allocations within the range of study at 122 and 134 GHz as documented in Section 2.1.2 (Table 1). Whilst past use has been inhibited by equipment availability, ongoing experimentation, high performance frequency sources and innovative adaptation of commercial chipsets has led to growth in activity which can be currently categorised as:

- Weak-signal reception of Narrowband (e.g. CW-Morse, Single side-band (SSB) voice or narrow—band FM (NBFM) voice) terrestrial operations in harmonised sub-bands and through non-geostationary amateur satellite transponders;
- Growing use of wider bandwidth modes, such as Digital Amateur TV (DATV) and data links;
- Usage of fixed beacon transmitting stations for propagation research and equipment alignment.

In general, most amateur stations are currently portable low-power highly directional systems. In order to maximise long-range communications, operation is often from elevated locations where they can achieve terrestrial line of sight contacts up to 50 km. Antennas operate at elevated angles for satellite operations.

6.2 PARAMETERS FOR STUDIES

Recommendation ITU-R M.1732-2 [29], tables 1B, 2B and 3B provide generic characteristics of stations operating in the Amateur Service for use in sharing studies. However, they are not very specific for the 122 and 134 GHz frequency ranges. The present Report uses the appropriate Amateur and Amateur-Satellite Service characteristics from those summarised in Table 32.

Terrestrial stations in the Amateur Service and Amateur-Satellite Services have identical technical characteristics, except for the (variable) positive elevation angle of the receiver antenna.

Table 32: Examples of Amateur and Amateur-Satellite Service characteristics in the 122 and 134 GHz bands

Parameter	CW-Morse	SSB Voice	NBFM Voice	DATV
Receiver IF bandwidth (kHz)	0.5	2.7	15	4000
Feeder Loss (dB)	0–6 (typically 1)	0–6 (typically 1)	0–6 (typically 1)	0–6 (typically 1)
Antenna gain (dBi)	36–52 (typically 40)	36–52 (typically 40)	36–52 (typically 40)	36–52 (typically 40)
Antenna polarisation	Horizontal, vertical	Horizontal, vertical	Horizontal, vertical	Horizontal, vertical
Receiver Noise Figure (dB)	3–7 (typically 4)	3–7 (typically 4)	3–7 (typically 4)	3–7 (typically 4)

The protection criterion for Amateur Service has been assumed to be I/N=-6 dB.

6.3 OPERATIONAL SCENARIO

For terrestrial operations, amateur stations are usually tripod mounted around 2 to 5 m above ground and are rotatable in azimuth. The operating sites are usually in non-built-up locations on high ground with uncluttered visibility (for the amateur link).

Parameters of UWB applications were taken from section 2.1.3 and 2.2.3. Calculations were made using only the mean power of the UWB applications.

The free space propagation model was used to calculate the path loss on a flat terrain. In addition, 1 dB/km of gaseous attenuation due to oxygen and water vapour was used, based on Recommendation ITU-R P.676 [5]. Propagation parameters were noted on each plot and were kept constant for all analyses. It is recognised that these conditions may produce worst-case results, in particular since clutter and shielding will have an important impact on the propagation conditions.

6.4 METHODOLOGY

In the following, single interferer MCL calculations were done for an area around an Amateur Service receiver which is placed at the position (0,0) and directed to the right. The impact of a single interferer (directed towards the Amateur Service antenna in the azimuth) is calculated on each point of the area taking into account the antenna patterns, as defined in section 2.1.3.1 for EVR and omni-directional antennas for in-cabin radars, and as defined in ITU-R F.699 [23] for Amateur Service. A schematic view from the top is given in Figure 50.

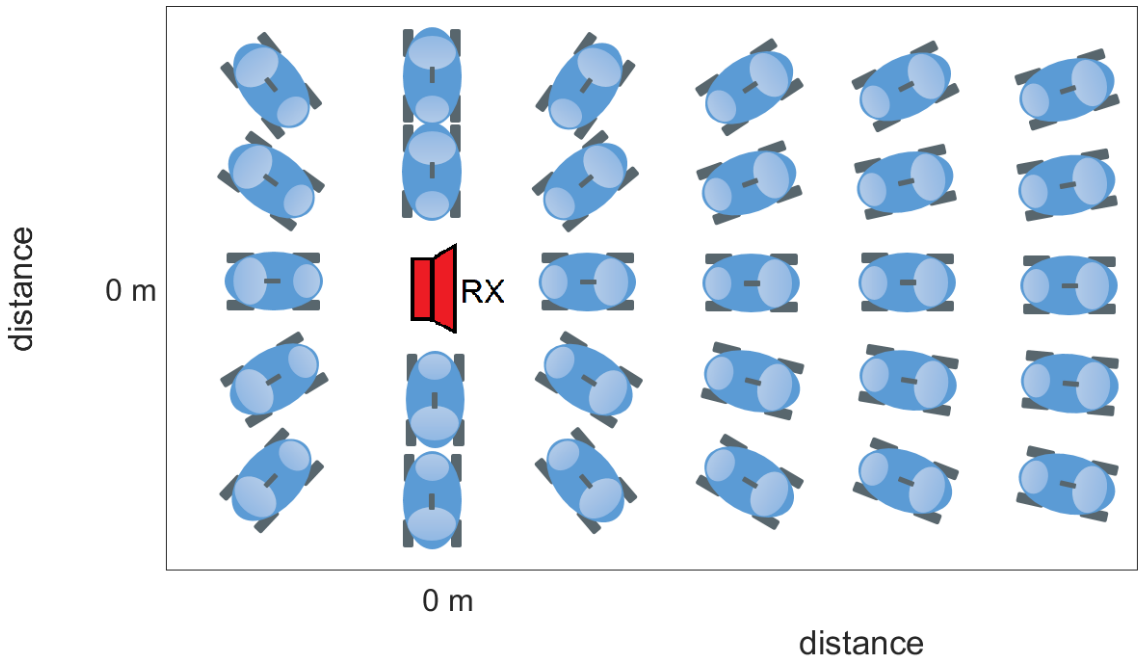


Figure 50: MCL scenario top view

Both antennas are pointing to 0° in elevation. A schematic view from the side is given in Figure 51, where the vertical separation between both systems is assumed to be 100 m and 300 m. It should be noted that it is assumed that the interferer is directed towards the Amateur Service antenna in the azimuth plane, meaning no differentiating azimuthal angle is applied, in contrast to the Report ITU-R M.2322-0 [34] where a de-pointing of 45° was also considered.

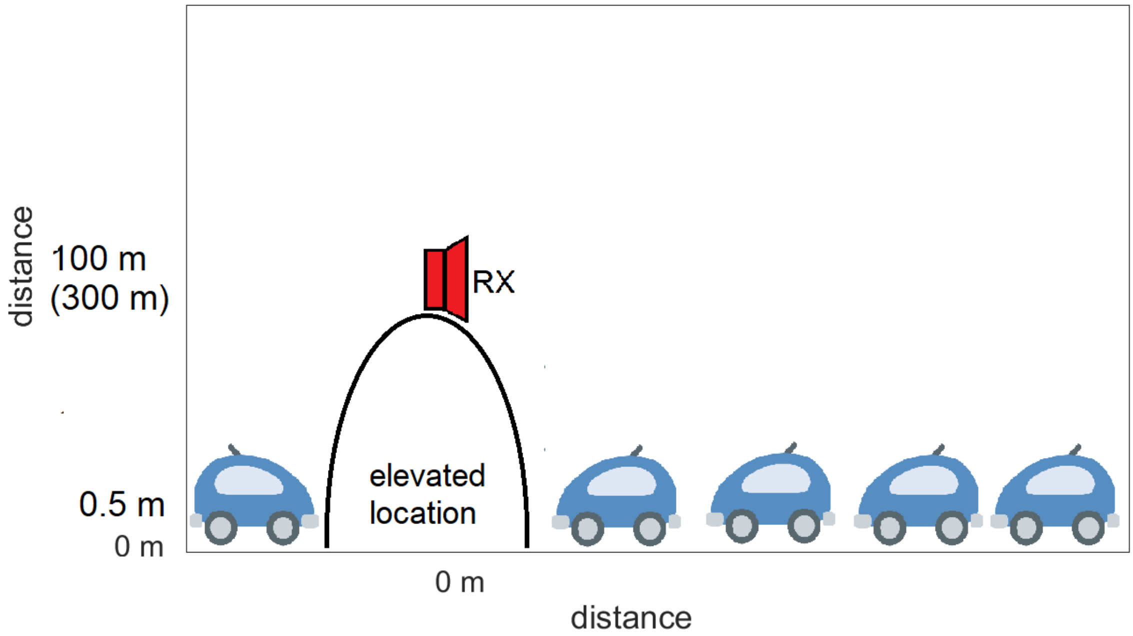


Figure 51: MCL with elevation scenario side view

The impact of a single interferer is calculated on each point of the area. The coloured areas highlight the amount to which the results lie above or below the criterion I/N =-6 dB. A red contour highlights the potential area where the I/N is above -6 dB. The parameters used and also the results are noted on the plots, respectively.

Peak radius results represent the maximum range of interference coming from the height level of the vehicular radar, when a constant ground level of 0 m is assumed. These situations are located in the main lobe pointing direction of the Amateur Service station.

Circle radius results represent the minimum range of interference coming from the height level of the vehicular radar, when a constant ground level of 0 m is assumed. This is usually located in the back lobe of the Amateur Service station.

Main beam to main beam results represent the MCL calculation, where no vertical nor horizontal geometry was considered. The calculations are also repeated for vertical height differences between the amateur station and the EVR of 100 m and 300 m.

The Radio-LOS distance represents the maximum distance for which LOS conditions would apply on a flat terrain.

6.5 RESULTS FOR EXTERIOR VEHICULAR RADARS

6.5.1 Exterior vehicular radar Type ”front” @5 dBm/MHz, Rx gain of 52 dBi

For very directive Amateur Service antennas with the maximum gain of 52 dBi, the calculation for a worst case geometry (main beam to main beam) for the EVR Type “front” would lead to a potential separation distance of 14.5 km, but this does not take into account the possible vertical and horizontal separation, as well as clutter/shielding.

Taking into account the vertical delta of 99.5 m and the respective antenna patterns, no separation distance is needed (see Figure 54).

Taking into account the vertical delta of 299.5 m and the respective antenna patterns, no separation distance is needed (see Figure 55).

The area of highest impact to the amateur radio receiver is limited to a small angle around its azimuthal directivity.

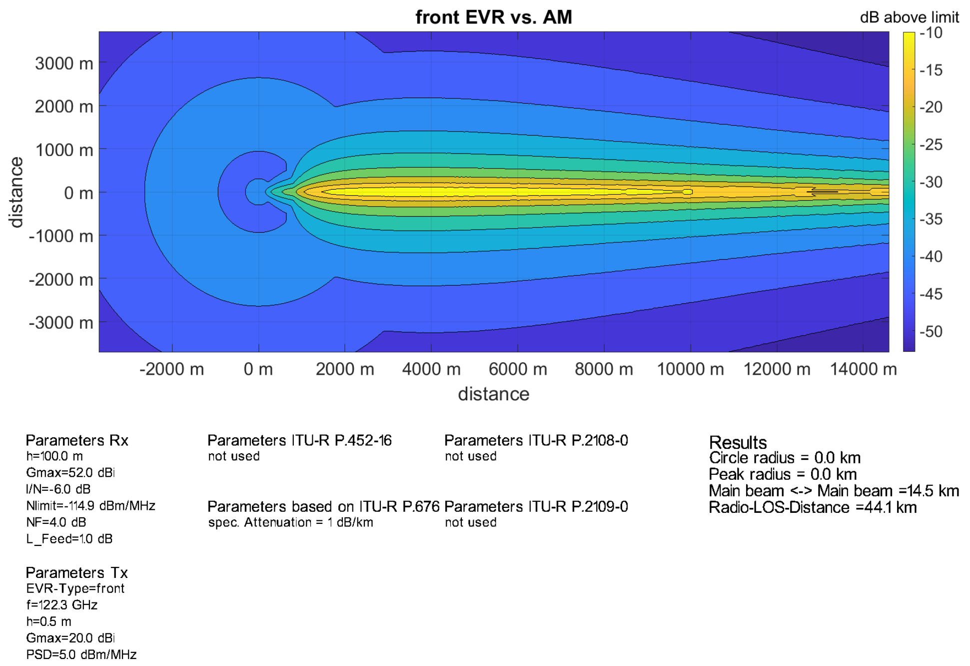


Figure 52: Results for front EVR @5 dBm/MHz vs. Amateur Service @100 m elevation

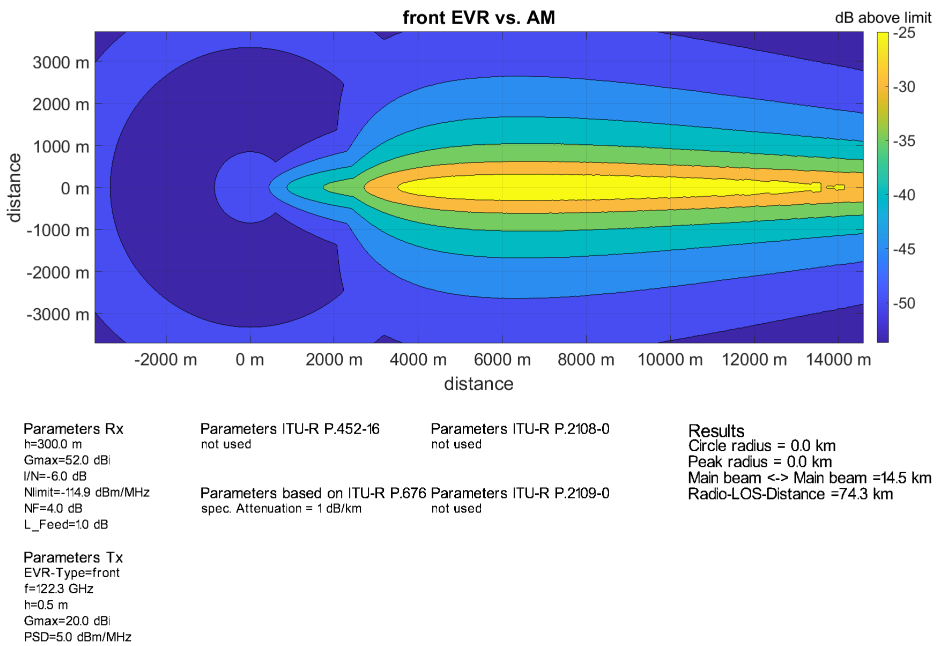


Figure 53: Results for front EVR @5 dBm/MHz vs. Amateur Service @300 m elevation

6.5.2 Exterior vehicular radar Type "front" @5 dBm/MHz, Rx gain of 40 dBi

For typical Amateur Service antennas with the maximum gain of 40 dBi, the worst-case geometry (main beam to main beam) for the EVR Type "front" would lead to a potential separation distance of 7.9 km, but this does not take into account the possible vertical and horizontal separation, as well as clutter/shielding.

Taking into account the vertical delta of 99.5 m and the respective antenna patterns, the potential separation distance was calculated to be 5.4 km (see Figure 54).

Taking into account the vertical delta of 299.5 m and the respective antenna patterns, no separation distance is needed (see Figure 55).

The area in which the interference to the amateur radio receiver would be higher than -6 dB I/N is limited to a small angle around its azimuthal directivity.

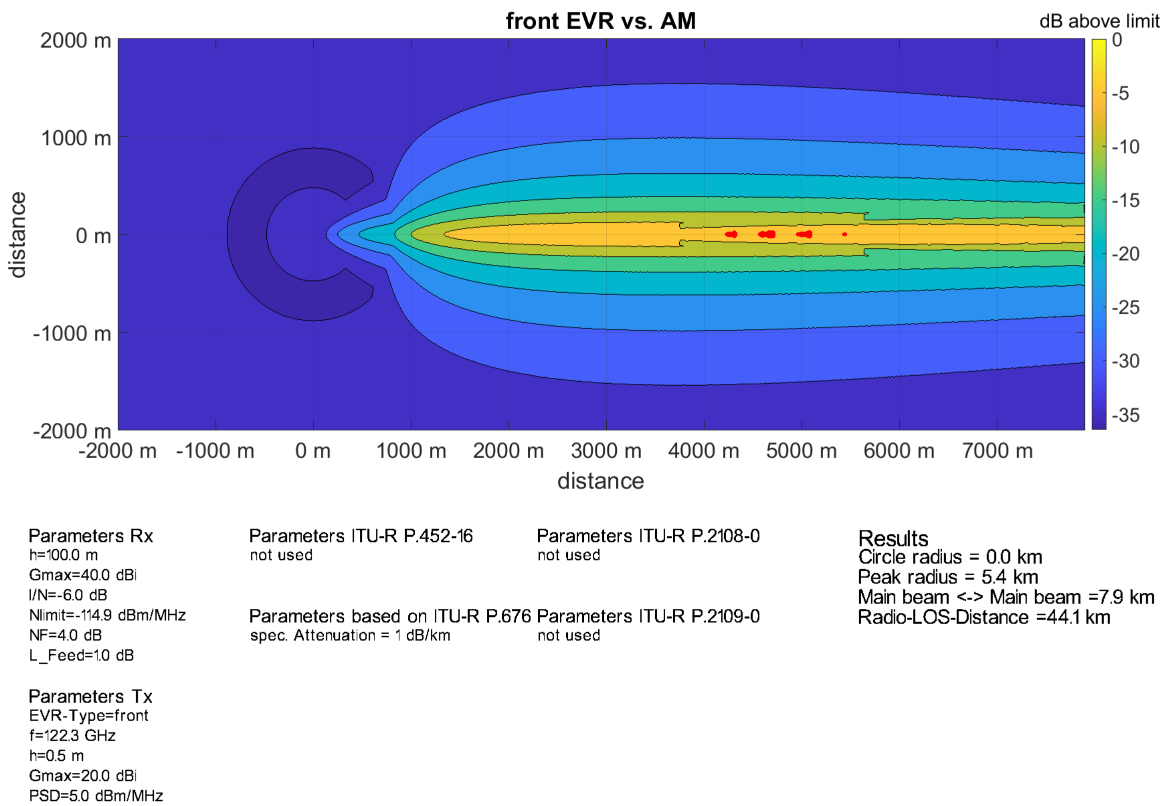


Figure 54: Results for front EVR @5 dBm/MHz vs. Amateur Service @100 m elevation

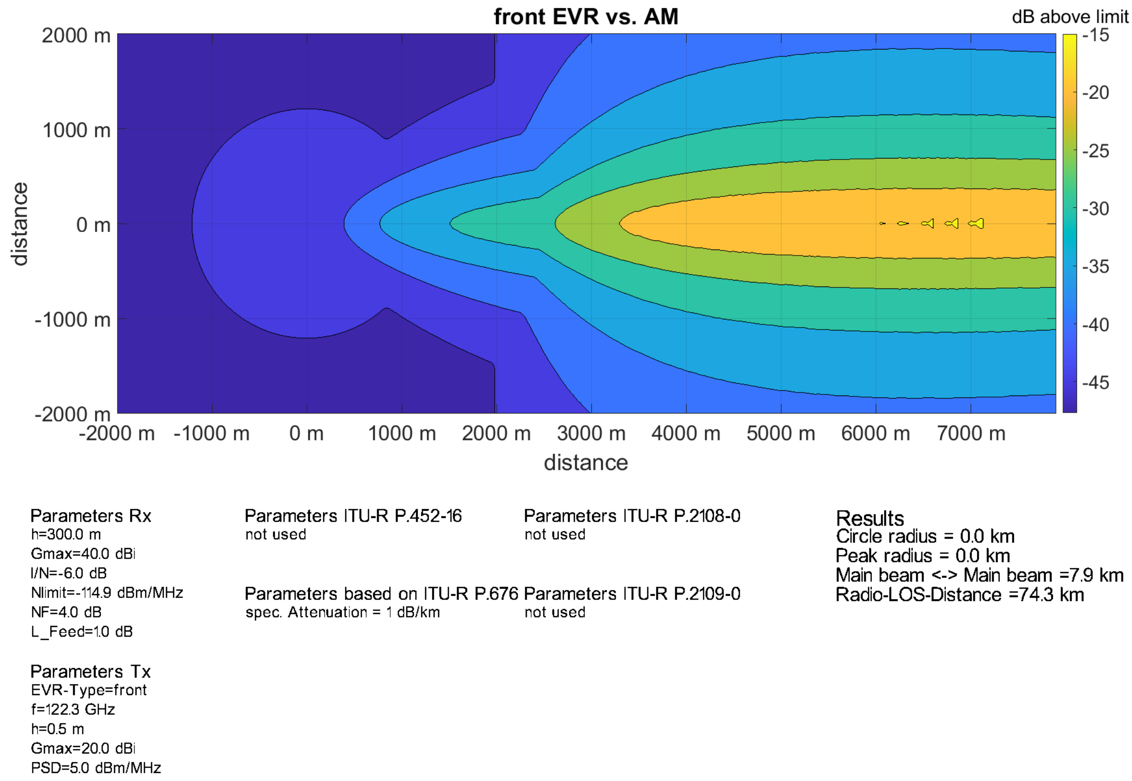


Figure 55: Results for front EVR @5 dBm/MHz vs. Amateur Service @300 m elevation

6.5.3 Exterior vehicular radar Type ”corner” and "short/ultra-short" @-15 dBm/MHz, Rx gain of 52 dBi

For Amateur Service antennas with the maximum gain of 52 dBi, the worst case geometry (main beam to main beam) for the EVR Type “corner” and "short/ultra-short" would lead to a potential separation distance of 4.6 km, but this does not take into account the possible vertical and horizontal separation, as well as clutter/shielding.

Taking into account the vertical delta of 99.5 m and the respective antenna patterns, no separation distance is needed (see Figure 54).

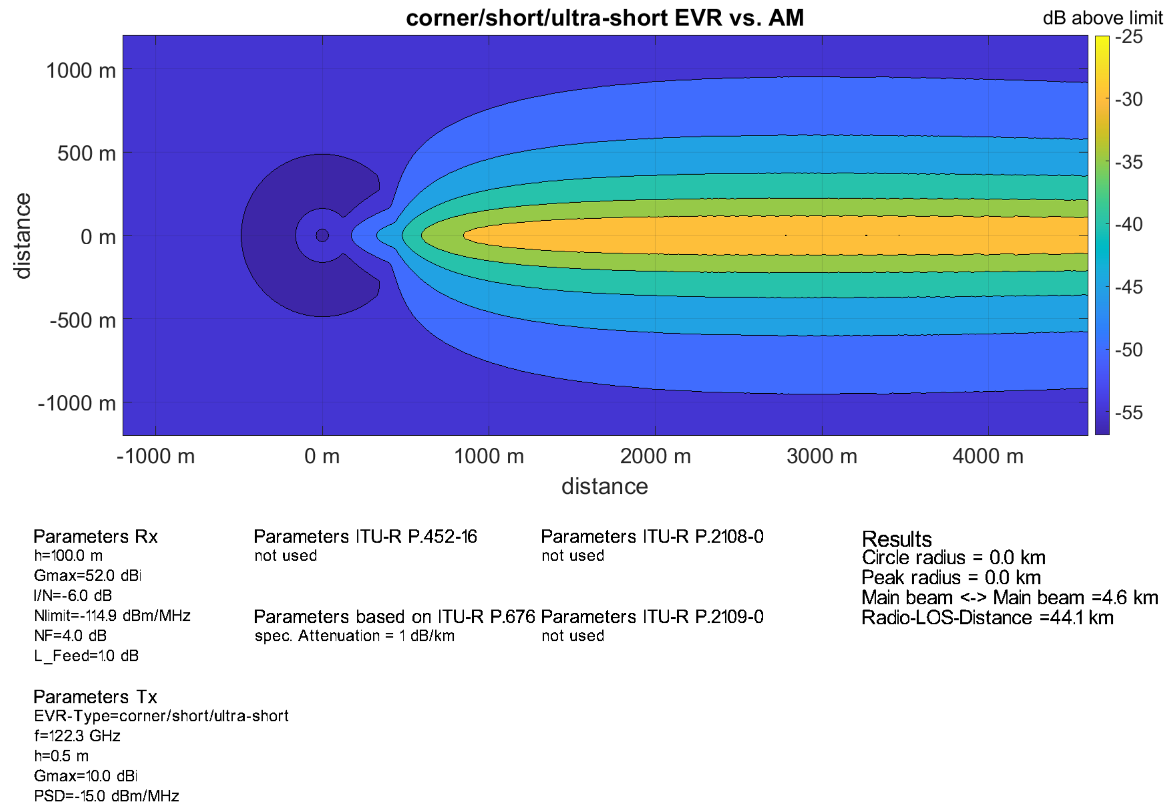


Figure 56: Results for corner/short/ultra-short EVR @-15 dBm/MHz vs. Amateur Service @100 m elevation

6.5.4 Exterior vehicular radar Type ”corner” and "short/ultra-short" @-15 dBm/MHz, Rx gain of 40 dBi

For typical Amateur Service antennas with the maximum gain of 40 dBi, the worst case geometry (main beam to main beam) for the EVR Type “corner” and "short/ultra-short" would lead to a potential separation distance of 1.6 km, but this does not take into account the possible vertical and horizontal separation, as well as clutter/shielding.

Taking into account the vertical delta of 99.5 m and the respective antenna patterns, no separation distance is needed (see Figure 56).

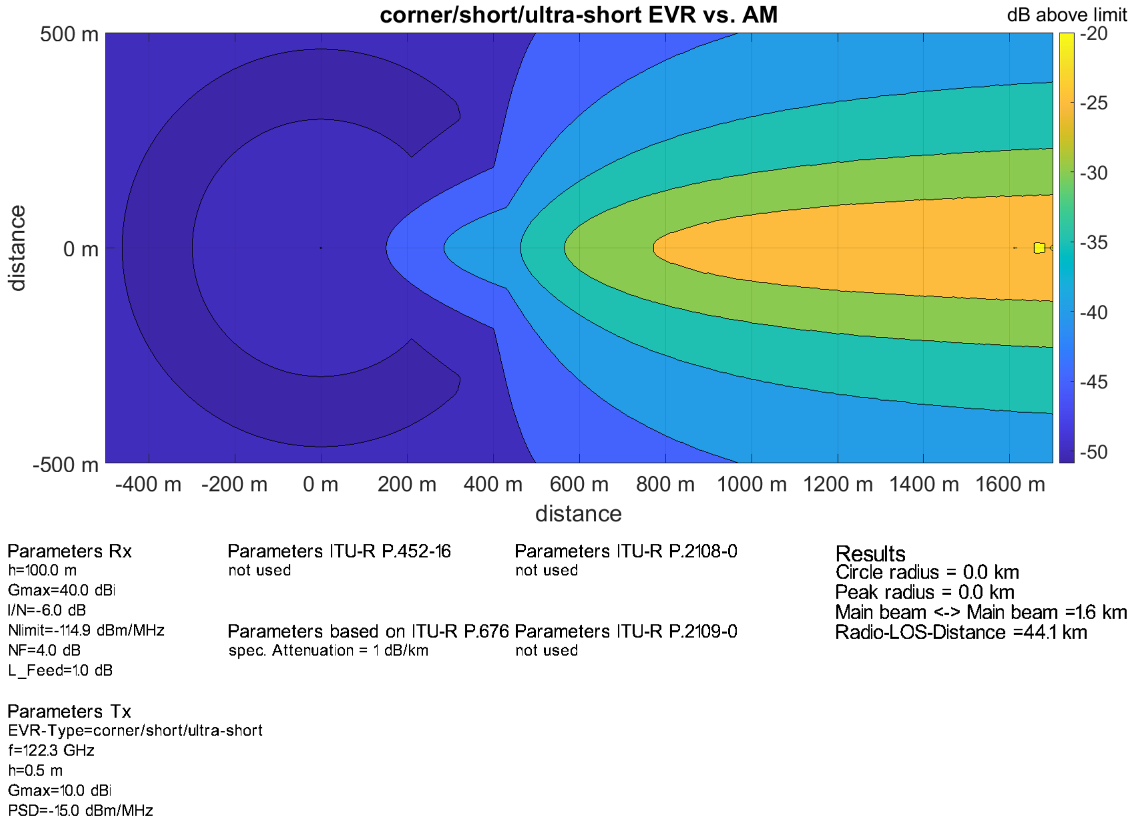


Figure 57: Results for corner/short/ultra-short EVR @-15 dBm/MHz vs. Amateur Service @100 m elevation

6.6 RESULTS FOR IN-CABIN VEHICULAR RADARS

6.6.1 In-cabin vehicular radar @-30 dBm/MHz, Rx gain of 52 dBi

For Amateur Service antennas with the maximum gain of 52 dBi, the worst case geometry (main beam to main beam) for the in-cabin vehicular radar would lead to a potential separation distance of 1.2 km, but this does not take into account the possible vertical and horizontal separation, as well as clutter/shielding.

Taking into account the vertical delta of 99.5 m and the respective antenna patterns, no separation distance is needed (see Figure 58).

These calculations did take account 15 dB (based on measurements given in Table 9) of additional attenuation between the in-cabin radar and the outdoor amateur radio station due to car body loss.

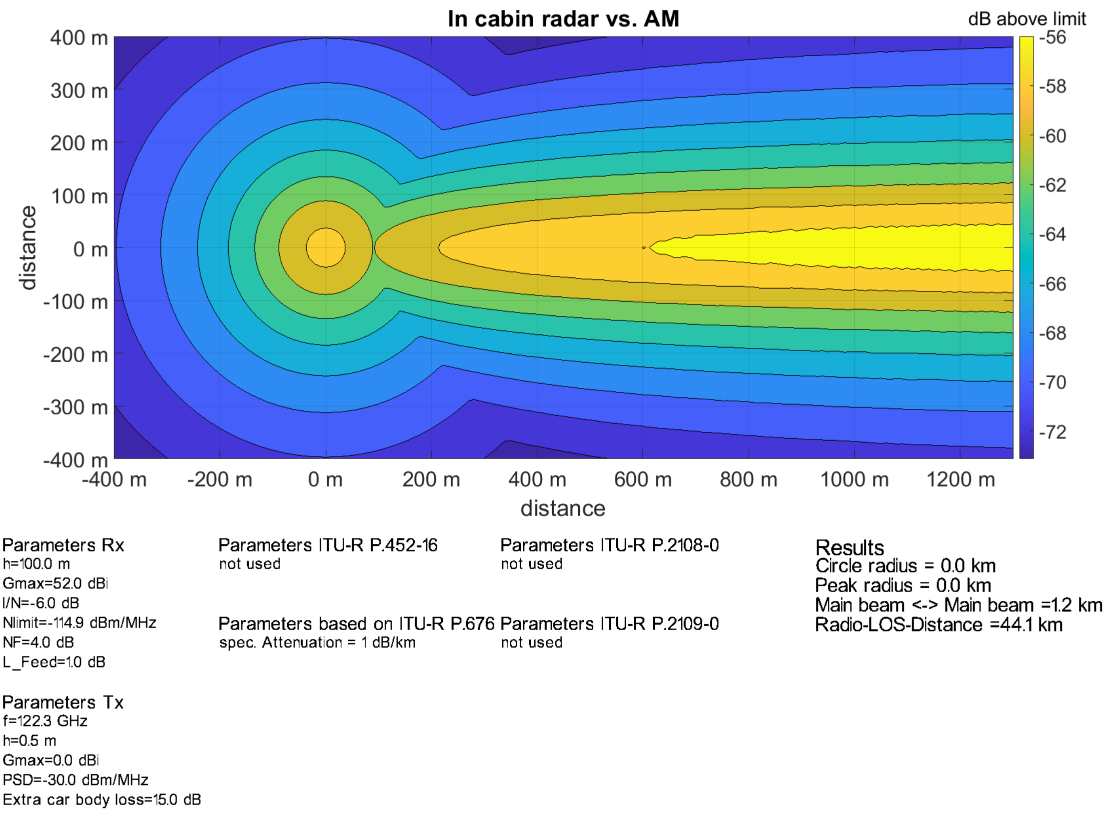


Figure 58: Results for in-cabin vehicular radar @-30 dBm/MHz vs. Amateur Service @100 m elevation

6.6.2 In-cabin vehicular radar @-30 dBm/MHz, Rx gain of 40 dBi

For typical Amateur Service antennas with the maximum gain of 40 dBi, the worst case geometry (main beam to main beam) for the in-cabin vehicular radar would lead to a potential separation distance of 0.3 km, but this does not take into account the possible vertical and horizontal separation, as well as clutter/shielding.

Taking into account the vertical delta of 99.5 m and the respective antenna patterns, no separation distance is needed (see Figure 56).

These calculations did take account 15 dB (based on measurements given in Table 9) of additional attenuation between the in-cabin radar and the outdoor amateur radio station due to car body loss.

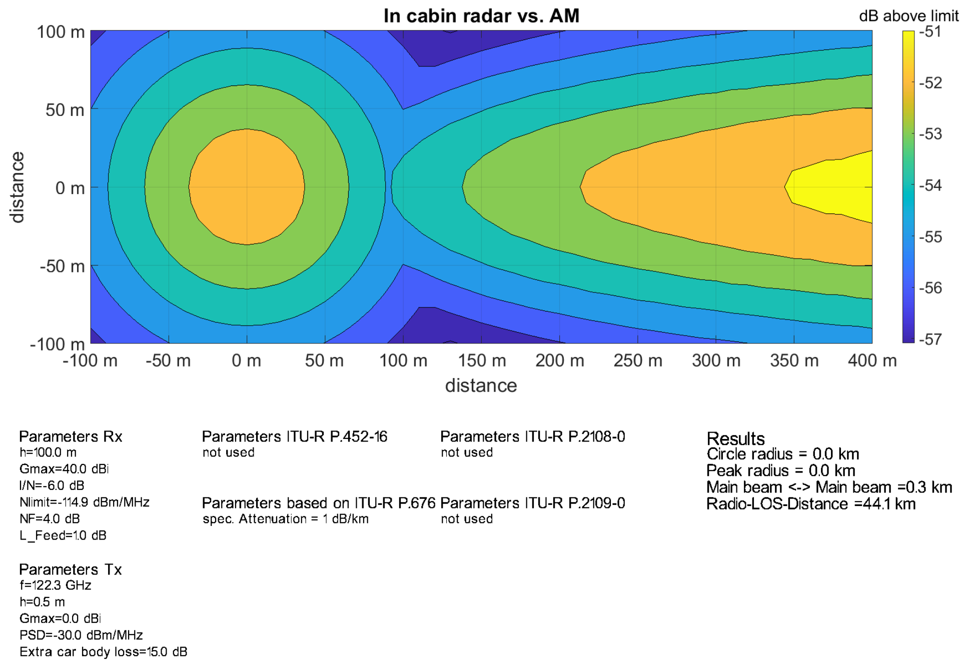


Figure 59: Results for in-cabin vehicular radar @-30 dBm/MHz vs. Amateur Service @100 m elevation

6.7 SUMMARY OF RESULTS

The results are summarised in Table 33 for 52 dBi Amateur Station Antenna, and in Table 34 for 40 dBi Amateur Station Antenna. The results related to main beam to main beam do not take into account the possible vertical and horizontal separation, as well as clutter/shielding.

Table 33: Summary of results, Amateur Station antenna @ 52 dBi

Amateur Station Antenna@52 dBi	EVR front	EVR corner/short/ultra-short	In-cabin vehicular radar
Main beam – Main beam	14.5 km	4.6 km	1.2 km
99.5 m vertical separation	0 km	0 km	0 km
299.5 m vertical separation	0 km	0 km	0 km

Table 34: Summary of results, Amateur Station antenna @ 40 dBi

Amateur Station Antenna@40 dBi	EVR front	EVR corner/short/ultra-short	In-cabin vehicular radar
Main beam – Main beam	7.9 km	1.6 km	0.3 km
99.5 m vertical separation	5.4 km	0 km	0 km
299.5 m vertical separation	0 km	0 km	0 km

6.8 CONCLUSIONS ON SHARING WITH AMATEUR SERVICE AND AMATEUR-SATELLITE SERVICE

For front EVR, MCL calculations reveal main beam to main beam separation distances of up to 14.5 km, but this does not take into account the possible vertical and horizontal separation, as well as clutter/shielding. Introducing 100 m of vertical separation into the same calculation, the distance reduces to 5.4 km. With 300 m of vertical separation, which may be difficult to achieve, the distance reduces to 0 km.

For corner or short/ultra-short EVR, MCL calculations reveal main beam to main beam separation distances of up to 4.6 km, but this does not take into account the possible vertical and horizontal separation, as well as clutter/shielding. With 100 m of vertical separation, the distance reduces to 0 km.

In general, the separation distance depends highly on transmission power level and angular offset (elevation and azimuth) between the vehicular radar transmitter to the amateur radio receiver. Due to the use of directive antennas the areas where interference to the amateur radio receiver would be higher than the protection criteria (-6 dB I/N) are limited to a small angle around amateur radio receiver's azimuthal directivity.

However, given the typical deployments of amateur stations in this frequency range, a critical and persistent worst-case alignment with the external vehicle radars is highly unlikely, due to natural mitigating factors such as:

- Road traffic has to be inside of the relatively narrow interference area;
- The car’s antenna must be directed towards the amateur station antenna;
- LOS conditions between EVR and the amateur station receiver must apply;
- Vertical separation between the amateur station location and the vehicle radars reduces the impact
- Typical duty cycles (50%) and frequency hopping techniques (effective additional DC factor of 25%) used by front-radars with high antenna gain, low bandwidth reduce the average interference into the amateur receiver. This may significantly reduce the impact on many amateur applications.
- Calculations are representative of a static situation whereas in a real dynamic situation, any potential interference will not be present all time;

Therefore, potential interference from external vehicular radars to the Amateur Service seems to be negligible in the bands 122.25-123 GHz and 134-141 GHz.

For in-cabin vehicular radars no interference could be found due to the low level of emissions and the body attenuation of the vehicle.

For the Amateur-Satellite Service operations, the antenna would be tilted skyward in which case the separation distances would be very much reduced due to side lobe coupling from the directional amateur station antenna. No specific studies of this scenario were deemed necessary.

Thus, it is concluded that in the bands 122.25-123 GHz and 134-141 GHz, coexistence between external and in-cabin vehicular radars and the Amateur and Amateur-Satellite Services can be achieved.

7 CONCLUSIONS

7.1 EXTERIOR VEHICULAR RADAR

7.1.1 Radio Astronomy

A single-interferer scenario compatibility study between Radio Astronomy Service (RAS) and radiodetermination devices for exterior vehicular radar has been conducted.

The study shows that separation distances are needed between the short-range devices and the observatories of NOEMA in France and IRAM 30 m in Spain in order to protect the RAS. These separation distances are dependent on the frequency and on the e.i.r.p. of the interfering short-range devices. The effectual mean e.i.r.p. of the SRDs which has been considered for this single-interferer study were 9 and 32 dBm in a bandwidth of 8 GHz, corresponding to the maximum power levels of corner and short/ultra-short radars, or front radars, respectively.

The study shows that separation distances around the radioastronomy sites of NOEMA in France for a maximum allowed mean e.i.r.p. level of 32 dBm in a bandwidth of 8 GHz, and IRAM 30 m in Spain for e.i.r.p. levels of 9 and 32 dBm in a bandwidth of 8 GHz have to be respected for the emissions of the radio determination devices for exterior vehicular radar.

An implementation of an automatic system to disable the transmission of the short-range device coupled with geo-positioning of the vehicle, referred to as “exclusion zone”, should be considered in order to protect the immediate vicinity (e.g. 3 km radius) of each RAS site.

An implementation of an automatic system to adapt the transmission parameters of the short-range device coupled with geo-positioning of the vehicle, referred to as “coordination zone”, should be considered in order to overcome compatibility issues. Several proposals for the definition of coordination zones are provided in ANNEX 3 for both NOEMA in France and IRAM 30 m in Spain. For the NOEMA site, the coordination zones design Option 4 is the recommended approach, as illustrated by Figure 19. For the IRAM 30 m site, the coordination zones design Option 3 is the recommended approach, as illustrated by Figure 20.

Although no aggregated studies were performed, it was expected that single entry studies provide a reasonable approximation.

7.1.2 Fixed Service

The single entry interference studies show that operation in the bands adjacent to fixed service is possible provided that the mean power densities in the fixed service bands are at most -33 dBm/MHz e.i.r.p. for the front radars and -36 dBm/MHz e.i.r.p. for the corner and short/ultra-short range radars. The corresponding peak power levels are 2 dBm e.i.r.p. within 1 GHz for the front radars and -1 dBm e.i.r.p. within 1 GHz for the corner and short/ultra-short range radars.

Co-channel operation in the 141-148.5 GHz band between the exterior vehicular radars and fixed services is only possible provided that the mean power densities are at most -33 dBm/MHz e.i.r.p. for the front radars and -36 dBm/MHz e.i.r.p. for the corner and short/ultra-short range radars. The corresponding peak power levels are 2 dBm e.i.r.p. within 1 GHz for the front radars and -1 dBm e.i.r.p. within 1 GHz for the corner and short/ultra-short range radars.

7.1.3 Earth Exploration Satellite Service (Passive)

For all investigated frequency ranges, the EESS (passive) protection criterion is satisfied for the considered aggregate scenarios, for any radar types, including aggregation of all radar types. Such results can be observed in Table 25, Table 26 and Table 27, as they exhibit positive margins. Under the assumed technical parameters defined in section 5.1, and the interference scenarios defined in section 5.2.3, it is concluded that compatibility of exterior vehicular radar can be ensured with EESS (passive).

Additional calculations have shown that a protection level of -49 dBm/MHz is required for the MWI system in the 116-122.25 GHz band as the most stringent requirement, while protection of system N1 outer in the 141-148.5 GHz band requires a protection level of -43.5 dBm/MHz.

Finally, in section 5.3.4, a proposal for limiting radars' unwanted emissions towards the EESS bands is provided, intending to regulate maximum transmit power in the unwanted emissions domain and antenna directivity to ensure compatibility with EESS in the adjacent bands, for radars operating in the 122.25-130 GHz band and for radars operating in the 134-148.5 GHz band.

7.1.4 Amateur and Amateur-Satellite Services

For front EVR, MCL calculations reveal main beam to main beam separation distances of up to 14.5 km, but this does not take into account the possible vertical and horizontal separation, as well as clutter/shielding. Introducing 100 m of vertical separation into the same calculation, the distance reduces to 5.4 km. With 300 m of vertical separation, which may be difficult to achieve, the distance reduces to 0 km.

For corner or short/ultra-short EVR, MCL calculations reveal main beam to main beam separation distances of up to 4.6 km, but this does not take into account the possible vertical and horizontal separation, as well as clutter/shielding. With 100 m of vertical separation, the distance reduces to 0 km.

In general, the separation distance depends highly on transmission power level and angular offset (elevation and azimuth) between the vehicular radar transmitter to the amateur radio receiver. Due to the use of directive antennas the areas where interference to the amateur radio receiver would be higher than the protection criteria (-6 dB I/N) are limited to a small angle around amateur radio receiver's azimuthal directivity.

However, given the typical deployments of amateur stations in this frequency range, a critical and persistent worst-case alignment with the external vehicle radars is highly unlikely, due to natural mitigating factors such as:

- Road traffic has to be inside of the relatively narrow interference area;
- The car's antenna must be directed towards the amateur station antenna;
- LOS conditions between EVR and the amateur station receiver must apply;
- Vertical separation between the amateur station location and the vehicle radars reduces the impact
- Typical duty cycles (50%) and frequency hopping techniques (effective additional DC factor of 25%) used by front-radars with high antenna gain, low bandwidth reduce the average interference into the amateur receiver. This may significantly reduce the impact on many amateur applications.
- Calculations are representative of a static situation whereas in a real dynamic situation, any potential interference will not be present all time;

Therefore, potential interference from external vehicular radars to the Amateur Service seems to be negligible in the bands 122.25-123 GHz and 134-141 GHz.

For the Amateur-Satellite Service operations, the antenna would be tilted skyward in which case the separation distances would be very much reduced due to side lobe coupling from the directional amateur station antenna. No specific studies of this scenario were deemed necessary.

Thus, it is concluded that in the bands 122.25-123 GHz and 134-141 GHz, coexistence between external vehicular radars and the Amateur and Amateur-Satellite Services can be achieved.

7.1.5 Summary

The following conditions need to be fulfilled for coexistence:

In the band 116-122.25 GHz, EESS (passive) band, compatibility with EESS (passive) determines the allowable unwanted emissions, up to -50 dBm/MHz mean e.i.r.p. density and -76 dBm/MHz maximum e.i.r.p. density above 35 degrees elevation for duty cycles ≤50%, and up to -53 dBm/MHz mean e.i.r.p. density and -79 dBm/MHz maximum e.i.r.p. density above 35 degrees elevation for duty cycles >50%;

In the bands 122.25-130 GHz and 134-141 GHz, sharing with RAS determines the operating conditions. Outside the coordination and exclusion zones, front radars can have a mean e.i.r.p up to 32 dBm in a bandwidth of 8 GHz, while corner and short/ultra-short range radars can have up to 9 dBm mean e.i.r.p. in 8 GHz.

Between 130-134 GHz, compatibility with fixed services is the most critical. This is possible with:

- Maximum mean power spectral density of -33 dBm/MHz e.i.r.p. for the front radars;
- Maximum mean power spectral density of -36 dBm/MHz e.i.r.p. for the corner and short/ultra-short range radar.

In the band 141-148.5 GHz, sharing with fixed services determines the operating conditions. The maximum wanted emissions requirements for all types of radar are:

- a Max.power spectral density (PSD) of -36 dBm/MHz e.i.r.p.;
- -6 dBm mean e.i.r.p. within 1 GHz;
- -1 dBm peak e.i.r.p. within 1 GHz.

Finally, for the band 148.5-151 GHz, compatibility with EESS (passive) determines the allowable out-of-band emissions, up to -44 dBm/MHz mean e.i.r.p. density and up to -70 dBm/MHz mean e.i.r.p. density above 35 degrees elevation for duty cycles ≤50%, and up to -47 dBm/MHz mean e.i.r.p. density and up to -73 dBm/MHz mean e.i.r.p. density above 35 degrees elevation for duty cycles >50%.

7.2 IN-CABIN VEHICULAR RADAR

7.2.1 Radio Astronomy

A single interferer scenario compatibility study between Radio Astronomy Service and in-cabin radar was conducted.

The calculated regions of zero margin for RAS stations IRAM 30 m in Spain and NOEMA in France are very limited and include only direct vicinity of both radio stations. No public roads or residential areas are located within the zero margin areas. However, in order to ensure protection of RAS stations it is proposed to define an exclusion zone in direct vicinity of each of radio station.

Radio telescope community indicated the need to protect the immediate vicinity (e.g. 3 km radius around the RAS) of both telescopes with a very stringent power limit (ideally a switch-off), since it is possible that people would drive cars up to the telescope even in absence of public roads or bring cars up to the RAS using cable car.

An implementation of an automatic system to disable transmission of in-cabin radar devices coupled with geo-positioning of the vehicle, referred as “exclusion zone”, should be considered in order to protect immediate vicinity of each RAS station. An exclusion zone is defined as a geographical area (typically the area within a circle with e.g. 3 km radius) within which the transmit operation of the radar equipment is automatically disabled (without manual intervention from the driver of the vehicle) to ensure no disturbance is generated towards a RAS in immediate vicinity.

The study showed that additional separation distances, beside exclusion zones in direct vicinity of RAS stations, are not needed between in-cabin vehicular radar and observatories NOEMA in France and IRAM 30 m in Spain.

Although no aggregated studies were performed, it was expected that single entry studies provide a reasonable approximation of a worst-case scenario.

7.2.2 Fixed Service

The single entry interference studies show that sharing between in-cabin vehicular radars and fixed services is possible for the considered in-band power level of 3 dBm mean e.i.r.p. and 16 dBm peak e.i.r.p. within a bandwidth of 1 GHz. For adjacent band compatibility studies, a 20 dB out-of-band attenuation was assumed, leading to -17 dBm mean e.i.r.p. and -4 peak e.i.r.p. in 1 GHz and hence showing compatibility.

7.2.3 Earth Exploration Satellite Service (Passive)

Results of the studies show that, for both single entry and aggregated interference scenarios, the protection of the EESS (passive) would be ensured for in-cabin radar operating in the adjacent frequency bands 122.25-130 GHz and 141-148.5 GHz. On the other hand, the case of the protection of the EESS (passive) from in-cabin radar operating co-frequency in the frequency band 116-130 GHz depicts large negative margins for aggregated study for the band 116-122.25 GHz.

No mitigation technique has been determined that could be considered to ensure the protection of EESS from in-cabin radar in the aggregated effect in the 116-122.25 GHz band. Therefore, the coexistence cannot be ensured with in-cabin radars.

For in-cabin radar working in frequency bands 122.25-130 GHz and 134-148.5 GHz, the following technical conditions could apply (on per radar basis):

Band 122.25-130 GHz:

- Maximum (mean) e.i.r.p. density in adjacent (EESS) band 116-122.25 GHz: -45 dBm/MHz;
- Downwards antenna orientation;
- Report shows that sensors integrated in conventional cars or cars with sunroof ensure at least 15 dB of exit-loss (attenuation) from the radar main beam to the EESS (passive) sensors' directions. In other cases, e.g. convertible cars, the minimum of 15 dB exit-loss (in worst case) needs to be proven. Process of proving is to be specified and agreed.

Band 134–148.5 GHz:

- Maximum (mean) e.i.r.p. density in adjacent (EESS) band 148.5-151 GHz: -39 dBm/MHz;
- Downwards antenna orientation;
- Report shows that sensors integrated in conventional cars or cars with sunroof ensure at least 15 dB of exit-loss (attenuation) from the radar main beam to the EESS (passive) sensors' directions. In other cases, e.g. convertible cars, the minimum of 15 dB exit-loss (in worst case) needs to be proven. Process of proving is to be specified and agreed.

7.2.4 Amateur and Amateur-Satellite Services

For in-cabin vehicular radars no interference could be found due to the low level of emissions and the body attenuation of the vehicle.

Thus, it is concluded that in the bands 122.25-123 GHz and 134-141 GHz, coexistence between in-cabin vehicular radars and the Amateur and Amateur-Satellite Services can be achieved.

7.2.5 Summary

The following conditions need to be fulfilled for coexistence.

For the in-cabin vehicular radar, the candidate frequency bands 116-130 GHz, 134-141 GHz and 141-148.5 GHz have been studied. The result of the studies showed that compatibility between in-cabin radar and investigated services in frequencies 122.25-130 GHz, 134-141 GHz and 141-148.5 GHz can be ensured under the technical assumptions used in the studies. In the light of this results of the studies it is likely that the 134-148.5 GHz range can be considered as a single band since all assumptions used and the calculations made for 134-141 GHz and 141-148.5 GHz bands are same.

In most frequency bands, EESS (passive) is the critical service determining the conditions under which compatibility is possible. In the bands 122.25-130 and 134-148.5 GHz that implies:

- Downwards antenna orientation;

- "15 dB exit loss" from the radar main beam to the EESS (passive) sensors' directions;
- Maximum mean e.i.r.p density -30 dBm/MHz;
- Maximum mean e.i.r.p. 3 dBm over the bandwidth;
- Maximum peak e.i.r.p. 16 dBm over the bandwidth;
- Minimum 1 GHz bandwidth.

In the EESS (passive) band 116-122.25 GHz, radars´ unwanted emissions should stay below a maximum. mean e.i.r.p density. of -45 dBm/MHz and in the EESS (passive) band 148.5-151 GHz below -39 dBm/MHz.

In the 130-134 GHz band, only 20 dB out-of-band attenuation is required, corresponding to a maximum unwanted emission level of -17 dBm/GHz.

ANNEX 1: CAR ATTENUATION MEASUREMENTS AT 122.5 GHZ

A1.1 INTRODUCTION

This Annex summarises the car attenuation measurements that have been performed to assist to the sharing and compatibility studies for in-cabin radars. A large set of measurements were conducted, both for a car with sunroof and a car without sunroof.

In the following sections, the test set-up is detailed and a description of the various measurements is given. An example result is included and the values for use in sharing and compatibility studies are extracted.

A1.2 TEST SET-UP

A1.2.1 Coordinate system

The same coordinate system was used for all measurements which is shown in Figure 60. The middle of the coordinate system was set in the middle of the car's roof, on the height of the first seat row. The x position values are positive to the front of the car and negative to the back. The y values are positive for the right side of the car and negative for the left side.

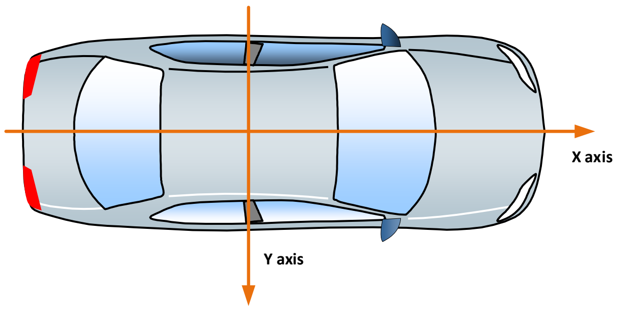


Figure 60: Coordinate system

A1.2.2 Sensor positions

There are four possible positions for the in-cabin radar sensors defined. These positions are: (1) over the second seat row, on the side between the door handle and B-pillar; either on the left side (2) or on the right side of the car (3), (4) middle of the car, slightly behind first row. Figure 61 shows these possible positions of the in-cabin radar sensors.

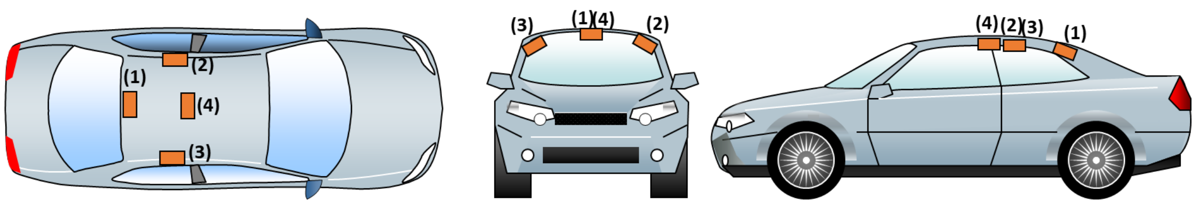


Figure 61: Possible positions of a radar sensor inside a car

For a car without sunroof all positions are considered. For a car with sunroof that can be opened, only position (1), (2) and (3) are considered.

A1.2.3 Set-up of the measurement

The in-cabin sensor was mounted inside of the car in one of the positions described in section A1.2.2. This sensor operates in the standard FMCW mode and has a broad antenna. It will be referred to as the transmit sensor. The second sensor is mounted on a pole that can be freely moved in x, y and z directions. The second sensor is set up to receive only at a frequency of 122.5 GHz. The sensor has a narrower antenna beam through the use of an additional antenna lens. This sensor will be referred to as the receive sensor.

Figure 62 shows an example set-up for the measurements.

The measurements were conducted with the receive sensor mounted with 90° angle (looking directly down to the ground), 35° angle and 0° angle.

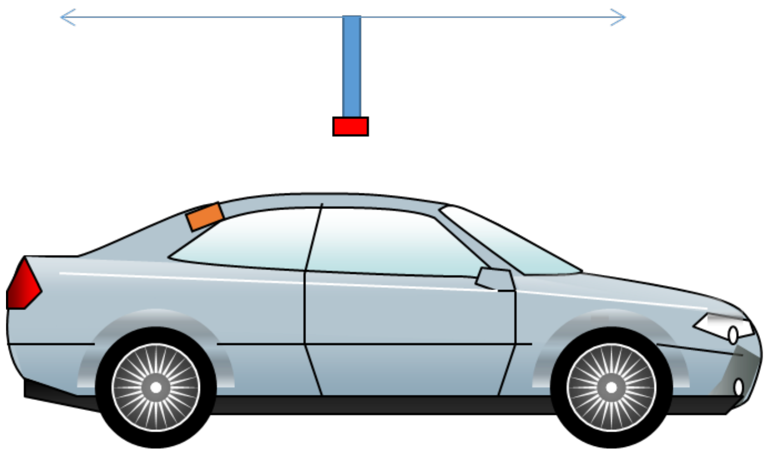


Figure 62: Test set-up with transmit sensor mounted inside the vehicle and receive sensor above the vehicle

Figure 53 shows the simulated antenna radiation pattern for the sensor mounted inside the vehicle.

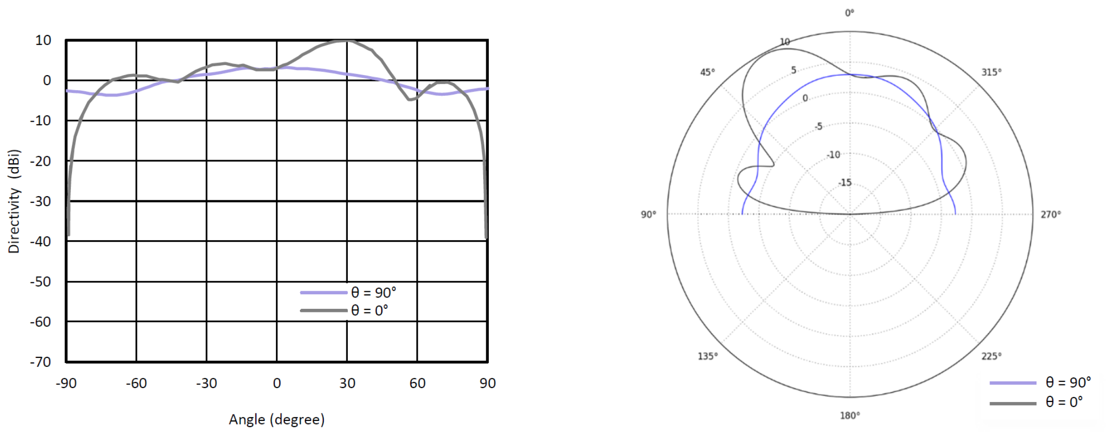


Figure 63: Antenna radiation pattern of the transmit sensor (simulated)

A1.2.4 Reference measurement

A reference measurement was conducted with the sensors looking directly at each other. The power received by the receive sensor was measured for various distances between sensors. The values between the measured points were interpolated.

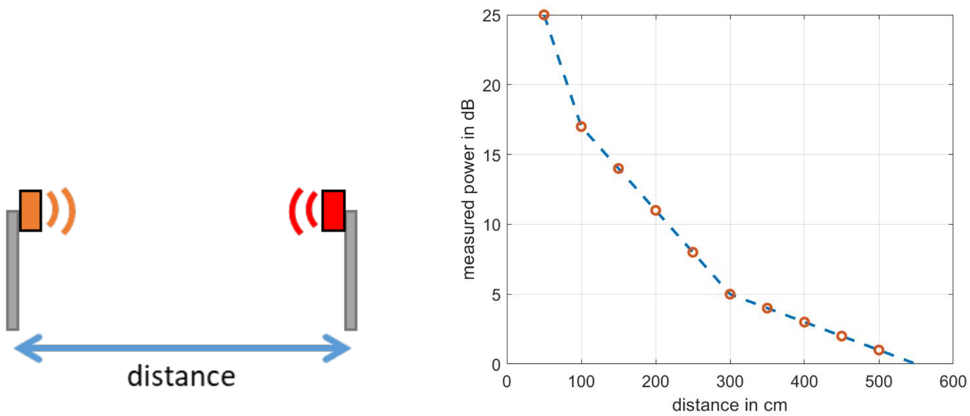


Figure 64: Left: test set up for reference measurement. The transmit and receive sensors were directly looking at each other. Right: reference measurement result. Red dots: measured values, blue line: interpolated curve

A1.2.5 Evaluation

The power received by the receive sensor, positioned outside the test car, from the sensor mounted inside the vehicle was evaluated. For each point, the distance between the two sensors was estimated. Results presented in following plots show the difference between the reference measurement and the power received from a sensor mounted inside the vehicle for the same distance between both sensors. The antenna patterns were not compensated.

A1.3 MEASUREMENTS

Measurements were conducted for a car with sunroof (Hyundai Genesis) and for a car with metallic roof (Renault Laguna). Measurements were conducted with all windows, including the sunroof if present, closed and then repeated with all windows, including the sunroof if present, open.

Three positions for the in-cabin radar were measured:

- position in the back of the car over the second seat row (1 in Figure 51);
- position on the left side next to door handle (2);
- position in the middle of the roof (4).

The position in the middle of the roof (4) was measured only for the metallic roof car.

Measurements were conducted with the position (1) of the transmit sensor over the second seat row. The receive sensor was mounted with an angle of 90°, 35° and 0°.

The measurement configuration for 90° mounting angle is shown in Figure 65. Five measurements along the length of the car and one across the middle of the car were performed. The receive sensor was moved slowly above the car. Figure 66 shows the set-up for 90° mounting measurements.

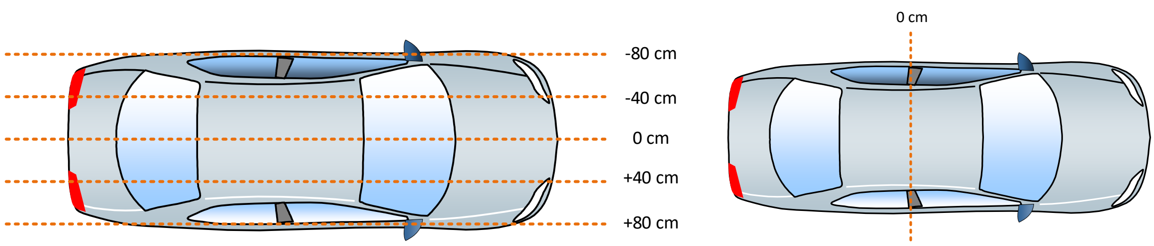


Figure 65: Measurements (left) along the car, and (right) across the car, for 90° receive sensor angle setting

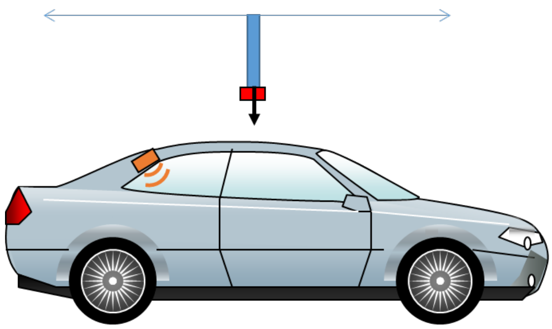


Figure 66: Test set-up for 90° receive sensor angle setting

Measurements for 35° mounting angle of the receive sensor were conducted from middle of the car to the front of the car, the back of the car, left or right side. The measurement front, back and side of the car require adjustment in mounting angle of the receive sensor. Following figures show the set-up for each of the measurements. The position of the sensor inside the car was the same as for measurements with 90° angle.

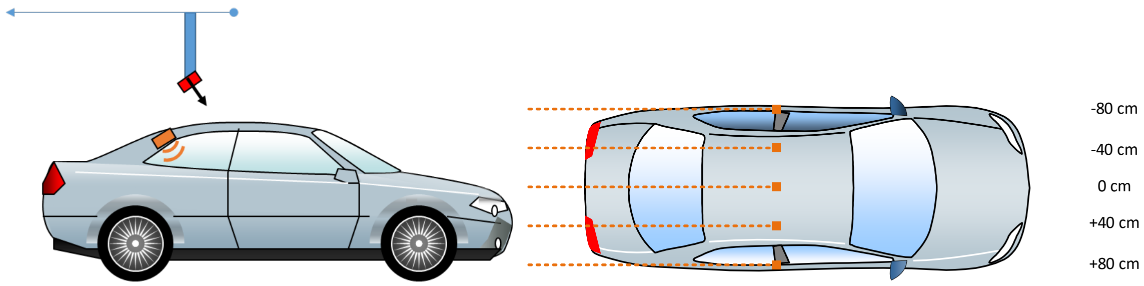


Figure 67: Measurement set-up for 35° angle for back of the car. The receive sensor is moved only up to the middle of the car

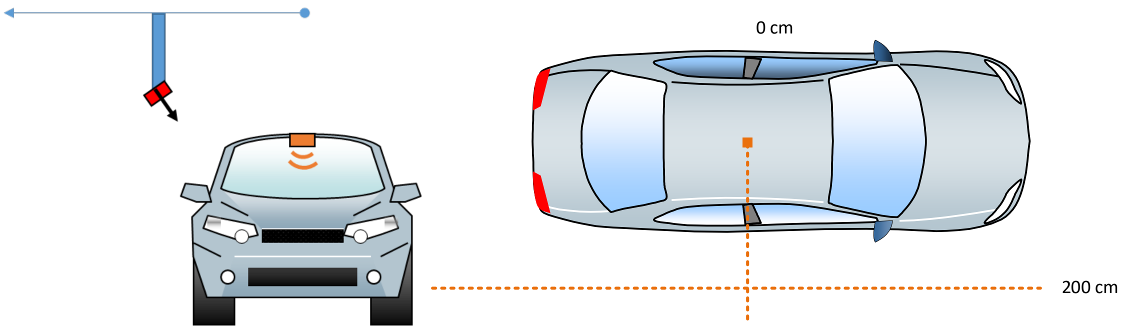


Figure 68: Measurement set-up for 35° angle for right side of the car. The receive sensor is moved from the middle of the car to the right. Additionally, a measurement along the car at 2 meters is conducted

Measurements for 0° were conducted on the side of each car. The receive sensor was adjusted to look directly to the car. The height of the receiver sensors was set same as the in-cabin sensor mounted inside car. The following figures show the set-up for these measurements.

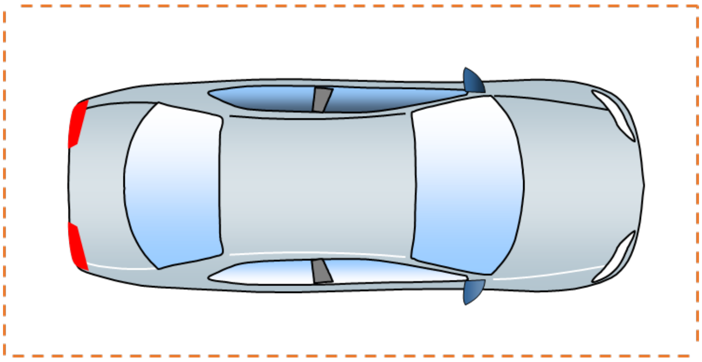


Figure 69: Measurement set-up for 0° angle. Measurement was conducted on right and left side of the car, from front and back

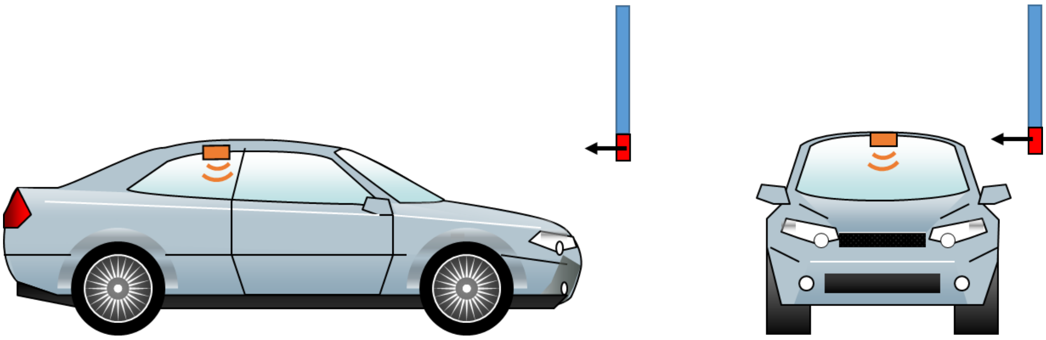


Figure 70: Measurement set-up 0° angle. Examples for measurement from front and left side of the car

A1.4 RESULTS

Results of one of the measurement sets are given in section A1.4.1 as an example.

For every line along the length of the car, the attenuation is recorded, both with the windows (and sunroof when present) either all open or closed. The results are shown in Figure 72 to Figure 76. From every measured curve, the minimum attenuation is extracted and listed in Table 33.

Sections A1.4.2, A1.4.3 and A1.4.4 contain mean, median, minimum and maximum attenuation for all measurements performed with 90, 35 and 0 degrees sensor angles respectively.

For use in the sharing and compatibility studies, single entry studies use the minimum of all minima as the worst-case value, while aggregate studies use the mean of all minimum values. These are listed in section A1.5.

A1.4.1 Example measurement results: car with sunroof, sensor position over the second seat row (1), along the back of the car with 35° angle

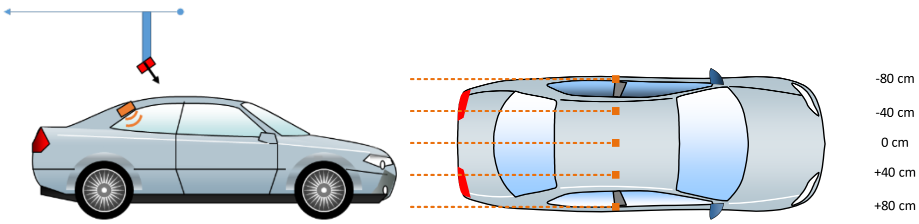


Figure 71: Measurement set-up

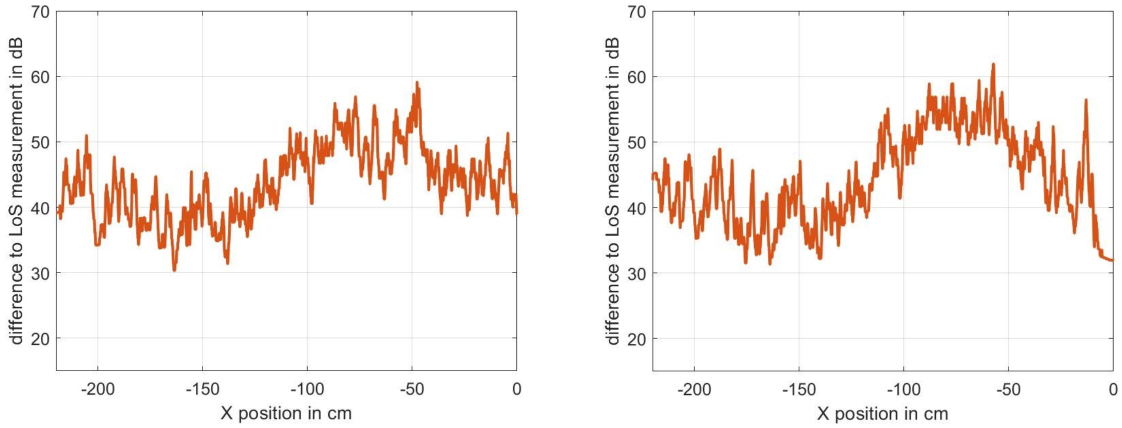


Figure 72: Measurement for 35°angle, X = -220 … 0 cm, Y = 0 cm, (left) windows and sunroof closed, (right) windows and sunroof opened

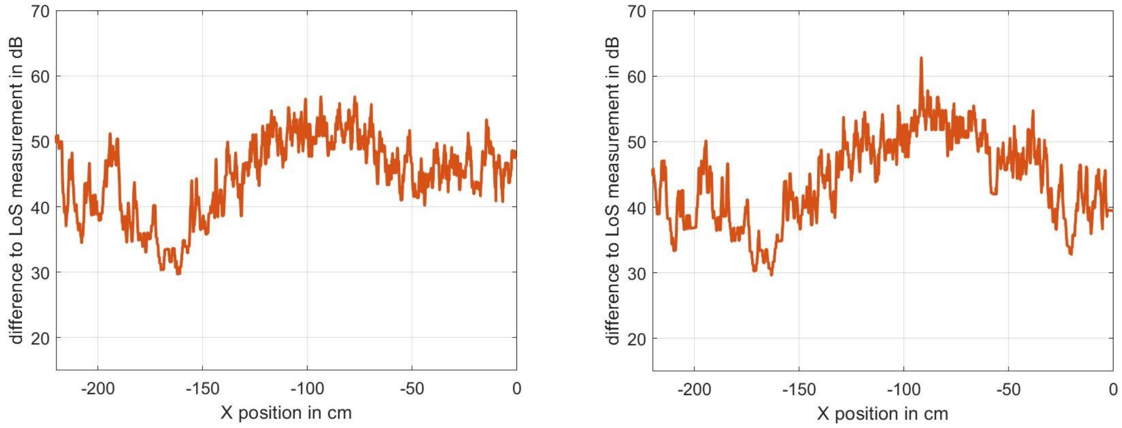


Figure 73: Measurement for 35° angle, X = -220 … 0 cm, Y = 40 cm, (left) windows and sunroof closed, (right) windows and sunroof opened

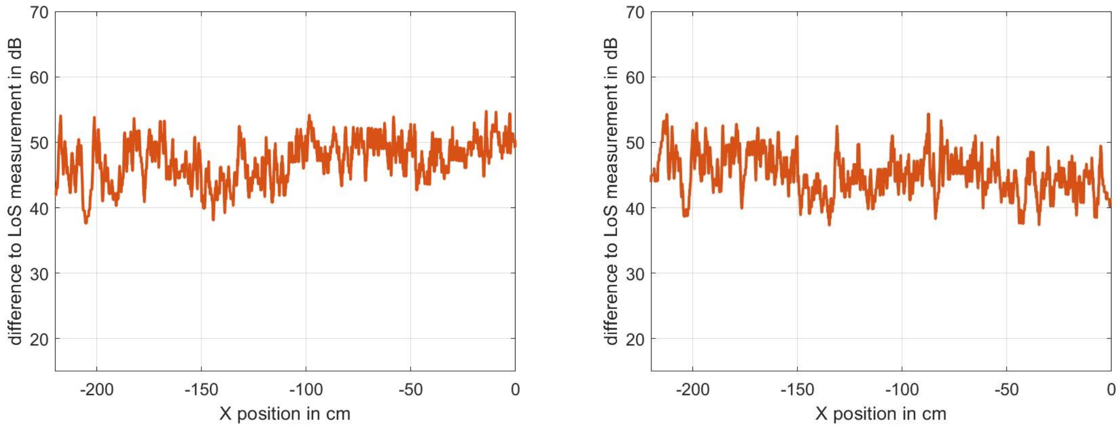


Figure 74: Measurement for 35° angle, X = -220 … 0 cm, Y = 80 cm, (left) windows and sunroof closed, (right) windows and sunroof opened

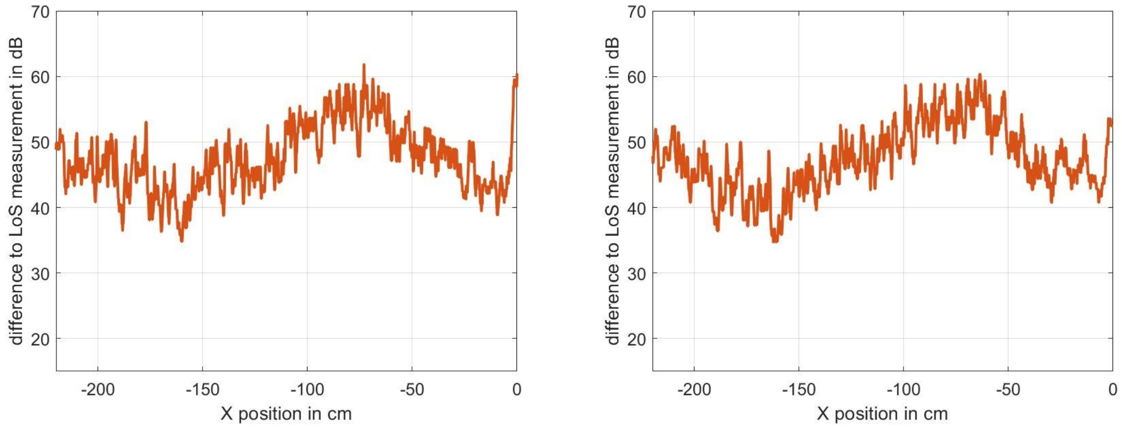


Figure 75: Measurement for 35° angle, X = -220 … 0 cm, Y = -40 cm, (left) windows and sunroof closed, (right) windows and sunroof opened

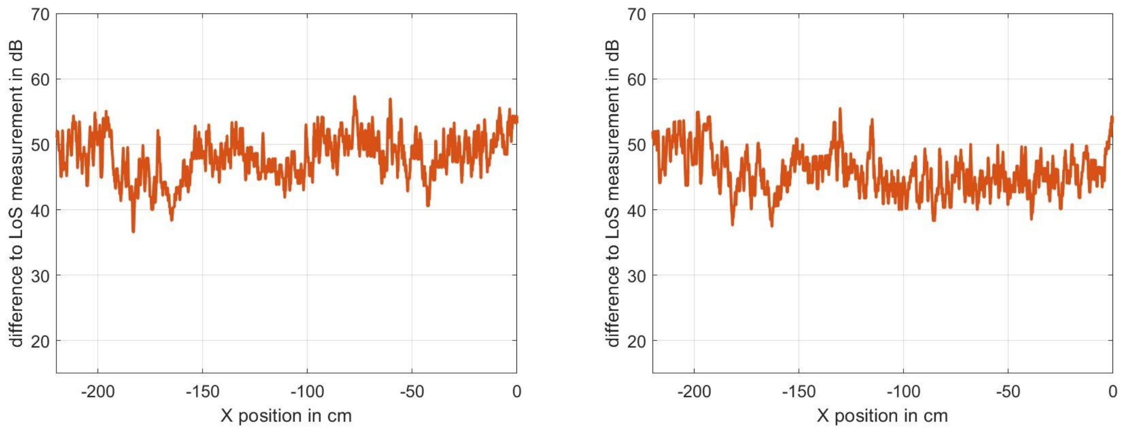


Figure 76: Measurement for 35° angle, X = -220 … 0 cm, Y = -80 cm, (left) windows and sunroof closed, (right) windows and sunroof opened

Table 35: Table with minimal values for each measurement for 35° along the back of the car measurements

Y position (cm)	Windows closed (dB)	Windows opened (dB)
0	30.3	31.3
+40	29.7	29..6
+80	37.6	37.3
-40	34.8	34.7
-80	36.6	37.4

A1.4.2 Summary of all measurement results with 90° angle

Table 36: Summary measurement results with 90° angle

Measurement file name	Attenuation (dB)			
	Mean	Median	Minimum	Maximum
Car with sunroof, sensor position back (1)				
Pos_back_90deg_X_-200_220_Y_-80_closed	47.22	48.64	37.98	60.24
Pos_back_90deg_X_-200_220_Y_-80_open	43.71	45.64	32.16	59.30
Pos_back_90deg_X_-200_220_Y_-40_closed	(no data)			
Pos_back_90deg_X_-200_220_Y_-40_open	43.46	45.86	33.20	60.20
Pos_back_90deg_X_-200_220_Y_0_closed	40.69	43.12	27.60	61.20
Pos_back_90deg_X_-200_220_Y_0_open	40.08	42.68	27.76	61.08
Pos_back_90deg_X_-200_220_Y_40_closed	41.77	43.68	32.64	58.78
Pos_back_90deg_X_-200_220_Y_40_open	40.45	43.40	29.70	60.04
Pos_back_90deg_X_-200_220_Y_80_closed	43.30	45.46	32.54	59.96
Pos_back_90deg_X_-200_220_Y_80_open	41.14	43.50	31.80	59.96
Pos_back_90deg_X_0_Y_-100_100_close	43.54	45.22	35.44	57.92
Pos_back_90deg_X_0_Y_-100_100_open	41.26	45.42	30.44	56.22
Car with sunroof, sensor position side left (2)				
MD_Genesis_90_p_X_-200_220_Y_-80_close	52.18	54.36	38.04	65.08
MD_Genesis_90_p_X_-200_220_Y_-80_open	49.45	51.60	36.68	59.34
MD_Genesis_90_p_X_-200_220_Y_-40_close	49.67	51.80	39.12	64.56
MD_Genesis_90_p_X_-200_220_Y_-40_open	49.24	50.88	37.82	64.72
MD_Genesis_90_p_X_-200_220_Y_0_close	44.29	46.56	32.28	58.12
MD_Genesis_90_p_X_-200_220_Y_0_open	44.48	46.65	32.20	57.28
MD_Genesis_90_p_X_-200_220_Y_40_close	42.82	45.24	31.40	56.50
MD_Genesis_90_p_X_-200_220_Y_40_open	43.09	45.08	33.92	56.38
MD_Genesis_90_p_X_-200_220_Y_80_close	40.65	42.70	28.18	54.34
MD_Genesis_90_p_X_-200_220_Y_80_open	37.86	40.73	26.94	55.36
MD_Genesis_90_p_X_0_Y_-100_100_close	48.41	50.04	39.46	66.96
MD_Genesis_90_p_X_0_Y_-100_100_open	42.56	50.40	28.64	70.88
Car with metallic roof, sensor position back (1)				

Measurement file name	Attenuation (dB)			
	Mean	Median	Minimum	Maximum
Laguna_pos_back_90deg_X_-200_220_Y_-80_close	47.36	48.11	40.04	60.76
Laguna_pos_back_90deg_X_-200_220_Y_-80_open	43.00	45.08	35.46	60.98
Laguna_pos_back_90deg_X_-200_220_Y_-40_close	48.26	52.36	38.22	64.48
Laguna_pos_back_90deg_X_-200_220_Y_-40_open2	46.88	52.41	37.26	62.48
Laguna_pos_back_90deg_X_-200_220_Y_0_close	49.59	53.88	39.80	65.04
Laguna_pos_back_90deg_X_-200_220_Y_0_open	49.73	54.78	38.12	64.84
Laguna_pos_back_90deg_X_-200_220_Y_40_close	42.50	45.00	32.58	66.00
Laguna_pos_back_90deg_X_-200_220_Y_40_open	42.81	45.68	33.46	65.68
Laguna_pos_back_90deg_X_-200_220_Y_80_close	42.77	45.00	33.50	59.36
Laguna_pos_back_90deg_X_-200_220_Y_80_open	40.55	43.06	30.58	57.92
Laguna_pos_back_90deg_X_-60_Y_-100_100_close	49.20	52.44	36.82	65.44
Laguna_pos_back_90deg_X_-60_Y_-100_100_open	47.93	51.94	35.64	65.44
Car with metallic roof, sensor position middle (4)				
Laguna_pos_middle_90deg_up_X_-160_260_Y_-80_close	45.55	47.00	36.42	63.74
Laguna_pos_middle_90deg_up_X_-160_260_Y_-80_open	41.78	43.22	32.72	62.38
Laguna_pos_middle_90deg_up_X_-160_260_Y_-40_close	45.15	57.10	32.58	66.80
Laguna_pos_middle_90deg_up_X_-160_260_Y_-40_open	45.21	54.74	33.78	67.44
Laguna_pos_middle_90deg_up_X_-160_260_Y_0_close	43.59	54.56	32.22	70.36
Laguna_pos_middle_90deg_up_X_-160_260_Y_0_open	43.10	53.84	31.22	66.68
Laguna_pos_middle_90deg_up_X_-160_260_Y_40_close	43.19	54.92	32.50	68.44
Laguna_pos_middle_90deg_up_X_-160_260_Y_40_open	42.44	54.80	30.50	66.44
Laguna_pos_middle_90deg_up_X_-160_260_Y_80_close	42.10	45.14	32.22	61.62
Laguna_pos_middle_90deg_up_X_-160_260_Y_80_open	40.03	41.64	31.44	60.90
Laguna_pos_middle_90deg_up_X_0_Y_-100_100_close	48.81	50.04	40.48	67.80
Laguna_pos_middle_90deg_up_X_0_Y_-100_100_open	44.94	49.52	31.94	66.96
Car with metallic roof, sensor position side left (2)				
Laguna_pos_sideL_90deg_X_-200_220_Y_-80_close	50.78	52.80	41.56	62.26
Laguna_pos_sideL_90deg_X_-200_220_Y_-80_open	46.87	49.91	36.44	57.96

Measurement file name	Attenuation (dB)			
	Mean	Median	Minimum	Maximum
Laguna_pos_sideL_90deg_X_-200_240_Y_-40_close	49.89	52.64	41.02	70.04
Laguna_pos_sideL_90deg_X_-200_220_Y_-40_open	50.33	52.25	40.98	67.88
Laguna_pos_sideL_90deg_X_-200_220_Y_0_closed3	48.82	50.62	40.96	67.00
Laguna_pos_sideL_90deg_X_-200_220_Y_0_open	49.79	55.76	39.76	67.16
Laguna_pos_sideL_90deg_X_-200_220_Y_40_close	47.32	49.02	39.14	61.46
Laguna_pos_sideL_90deg_X_-200_220_Y_40_open	46.74	48.22	39.26	58.82
Laguna_pos_sideL_90deg_X_-200_220_Y_80_close	43.25	45.72	33.42	54.42
Laguna_pos_sideL_90deg_X_-200_220_Y_80_open	40.10	43.07	31.48	53.08
Laguna_pos_sideL_90deg_X_0_Y_-100_100_closed	54.17	61.52	42.76	69.88
Laguna_pos_sideL_90deg_X_0_Y_-100_100_open	43.79	57.70	29.36	71.04

A1.4.3 Summary of all measurement results with 35° angle

Table 37: Summary of measurement results with 35° angle

Measurement file name	Attenuation (dB)			
	Mean	Median	Minimum	Maximum
Car with sunroof, sensor position back (1)				
Pos_back_35deg_X_-220_0_Y_-80_close	46.75	48.16	36.60	57.32
Pos_back_35deg_X_-220_0_Y_-80_open	44.66	45.44	37.44	55.46
Pos_back_35deg_X_-220_0_Y_-40_close	44.83	47.00	34.82	61.80
Pos_back_35deg_X_-220_0_Y_-40_open	44.51	47.00	34.70	60.32
Pos_back_35deg_X_-220_0_Y_0_closed	40.55	43.75	30.32	59.12
Pos_back_35deg_X_-220_0_Y_0_open	39.72	43.62	31.32	61.92
Pos_back_35deg_X_-220_0_Y_40_closed	40.23	45.71	29.70	56.80
Pos_back_35deg_X_-220_0_Y_40_open	39.78	44.76	29.64	62.80
Pos_back_35deg_X_-220_0_Y_80_closed	45.91	47.64	37.64	54.74
Pos_back_35deg_X_-220_0_Y_80_open	44.00	44.97	37.34	54.32
_Pos_back_35deg_front_X_0_240_Y_-80_closed	37.31	41.22	27.54	52.54
_Pos_back_35deg_front_X_0_240_Y_-80_open	33.95	36.78	25.66	49.08
_Pos_back_35deg_front_X_0_240_Y_-40_close	36.00	40.27	25.84	52.46
_Pos_back_35deg_front_X_0_240_Y_-40_open	33.71	36.18	24.52	51.92

Measurement file name	Attenuation (dB)			
	Mean	Median	Minimum	Maximum
_Pos_back_35deg_front_X_0_240_Y_0_closed	34.57	36.66	26.30	49.26
_Pos_back_35deg_front_X_0_240_Y_0_open	30.65	33.8	19.36	52.88
_Pos_back_35deg_front_X_0_240_Y_40_close	34.19	37.32	25.06	54.10
_Pos_back_35deg_front_X_0_240_Y_40_open	30.68	33.8	19.10	50.16
_Pos_back_35deg_front_X_0_240_Y_80_close	37.66	41.16	28.60	51.04
_Pos_back_35deg_front_X_0_240_Y_80_open	32.96	36.12	22.56	48.18
_Pos_back_35deg_sizeL_X_-200_200_Y_-200_close	38.72	41.6	28.30	55.78
_Pos_back_35deg_sizeL_X_-200_200_Y_-200_open	38.58	40.8	28.86	53.08
_Pos_back_35deg_sizeR_X_-200_200_Y_200_close	38.21	40.12	27.34	52.78
_Pos_back_35deg_sizeR_X_-200_200_Y_200_open	42.02	43.72	33.40	54.20
_Pos_back_35deg_sizeL_X_0_Y_-280_0_close	38.08	39.84	28.26	58.88
_Pos_back_35deg_sizeL_X_0_Y_-280_0_open	34.81	38.08	25.64	56.88
_Pos_back_35deg_sizeR_X_0_Y_0_280_close	40.85	43.42	29.38	56.88
_Pos_back_35deg_sizeR_X_0_Y_0_280_open	37.08	41.36	26.38	56.98
Car with sunroof, sensor position side left (2)				
MD_Genesis_35_back_p_X_-240_0_Y_-80_close	47.35	48.63	40.06	68.24
MD_Genesis_35_back_p_X_-240_0_Y_-80_open	42.91	45.08	34.24	61.08
MD_Genesis_35_back_p_X_-240_0_Y_-40_close	40.98	47.34	29.38	64.72
MD_Genesis_35_back_p_X_-240_0_Y_-40_open	41.22	48.46	30.02	63.48
MD_Genesis_35_back_p_X_-240_0_Y_0_close	38.91	41.68	29.50	54.36
MD_Genesis_35_back_p_X_-240_0_Y_0_open	38.75	41.88	28.68	55.06
MD_Genesis_35_back_p_X_-240_0_Y_40_close	39.69	42.38	30.58	52.42
MD_Genesis_35_back_p_X_-240_0_Y_40_open	39.43	42.34	29.40	53.52
MD_Genesis_35_back_p_X_-240_0_Y_80_close2	40.75	42.00	33.14	51.18
MD_Genesis_35_back_p_X_-240_0_Y_80_open	38.29	39.46	30.34	59.24
MD_Genesis_35_front_p_X_-20_240_Y_-80_close2	48.11	51.46	38.58	67.08
MD_Genesis_35_front_p_X_-20_240_Y_-80_open	43.87	46.64	33.76	61.76
MD_Genesis_35_front_p_X_-20_240_Y_-40_close	42.43	49.64	30.56	65.72
MD_Genesis_35_front_p_X_-20_240_Y_-40_open	41.83	45.94	30.80	69.40
MD_Genesis_35_front_p_X_-20_240_Y_0_close	41.81	43.58	31.06	61.20

Measurement file name	Attenuation (dB)			
	Mean	Median	Minimum	Maximum
MD_Genesis_35_front_p_X_-20_240_Y_0_open	38.15	41.70	27.06	62.20
MD_Genesis_35_front_p_X_-20_240_Y_40_close	41.05	43.04	31.94	54.34
MD_Genesis_35_front_p_X_-20_240_Y_40_open	37.35	38.60	28.72	62.34
MD_Genesis_35_front_p_X_-20_240_Y_80_close	38.31	40.66	30.26	60.18
MD_Genesis_35_front_p_X_-20_240_Y_80_open	32.79	36.44	22.64	53.14
MD_Genesis_35_side_R_p_X_-200_200_Y_200_close	27.06	29.96	18.90	50.48
MD_Genesis_35_side_R_p_X_-200_200_Y_200_open	24.85	30.16	15.64	51.42
MD_Genesis_35_side_R_p_X_0_Y_0_280_close	31.40	36.28	20.56	61.24
MD_Genesis_35_side_R_p_X_0_Y_0_280_open	26.64	32.02	15.04	67.20
(Measurements on left side missing)				
Car with metallic roof, sensor position back (1)				
Laguna_pos_back_35deg_back_X_-240_0_Y_-40_close	46.47	49.04	36.44	69.4
Laguna_pos_back_35deg_back_X_-240_0_Y_-40_open	48.42	50.96	38.50	68.44
Laguna_pos_back_35deg_back_X_-240_0_Y_-80_close	43.45	44.48	36.52	55.76
Laguna_pos_back_35deg_back_X_-240_0_Y_-80_open	40.41	41.96	33.52	51.76
Laguna_pos_back_35deg_back_X_-240_0_Y_0_close	38.65	46.74	27.54	71.80
Laguna_pos_back_35deg_back_X_-240_0_Y_0_open	37.98	46.78	26.42	71.80
Laguna_pos_back_35deg_back_X_-240_0_Y_40_close	45.30	50.68	34.92	69.24
Laguna_pos_back_35deg_back_X_-240_0_Y_40_open	44.12	48.94	35.4	68.96
Laguna_pos_back_35deg_back_X_-240_0_Y_80_close	43.75	45.8	36.2	56.00
Laguna_pos_back_35deg_back_X_-240_0_Y_80_open	41.71	44.28	33.16	56.94
Laguna_pos_back_35deg_front_X_0_260_Y_-40_close	37.37	46.62	26.92	63.48
Laguna_pos_back_35deg_front_X_0_260_Y_-40_open	37.40	45.52	28.06	63.16
Laguna_pos_back_35deg_front_X_0_260_Y_-80_close	39.71	43.42	28.52	60.10
Laguna_pos_back_35deg_front_X_0_260_Y_-80_open	35.03	38.44	25.58	55.16
Laguna_pos_back_35deg_front_X_0_260_Y_0_close	30.42	43.87	19.92	64.24
Laguna_pos_back_35deg_front_X_0_260_Y_0_open	30.62	45.08	19.52	62.76
Laguna_pos_back_35deg_front_X_0_260_Y_40_close	35.78	44.536	23.68	62.60
Laguna_pos_back_35deg_front_X_0_260_Y_40_open	37.46	46.47	25.38	61.6

Measurement file name	Attenuation (dB)			
	Mean	Median	Minimum	Maximum
Laguna_pos_back_35deg_front_X_0_260_Y_80_close	37.29	39.58	28.66	57.34
Laguna_pos_back_35deg_front_X_0_260_Y_80_open	33.40	35.15	23.24	50.86
Laguna_pos_back_35deg_sideL_X_-200_220_Y_-200_close	42.511 2	44.2	34.34	53.36
Laguna_pos_back_35deg_sideL_X_-200_220_Y_-200_open	38.27	40.04	28.34	51.94
Laguna_pos_back_35deg_X_-200_220_Y_200_close	46.85	47.46	40.40	55.92
Laguna_pos_back_35deg_X_-200_220_Y_200_open	43.05	43.55	37.3	55.10
Laguna_pos_back_35deg_X_-60_Y_0_280_close	45.76	51.92	33.96	67.92
Laguna_pos_back_35deg_sideR_X_-60_Y_0_280_open	45.84	52.08	34.76	64.76
Laguna_pos_back_35deg_sideL_X_-60_Y_-280_0_close	43.44	51.48	33.44	67.40
Laguna_pos_back_35deg_sideL_X_-60_Y_-280_0_open	44.85	47.20	34.62	68.40
Car with metallic roof, sensor position middle (4)				
Laguna_pos_middle_35deg_back_X_-210_30_Y_-80_close	46.86	47.67	40.46	58.76
Laguna_pos_middle_35deg_back_X_-210_30_Y_-80_open	44.03	44.93	37.76	53.68
Laguna_pos_middle_35deg_back_X_-210_30_Y_-40_close	46.97	52.08	35.04	66.20
Laguna_pos_middle_35deg_back_X_-210_30_Y_-40_open	45.98	53.51	37.84	66.20
Laguna_pos_middle_35deg_back_X_-210_30_Y_0_close	44.51	52.64	36.44	69.92
Laguna_pos_middle_35deg_back_X_-210_30_Y_0_open	43.81	51.02	35.94	68.92
Laguna_pos_middle_35deg_back_X_-210_30_Y_40_close	46.06	52.92	36.86	64.20
Laguna_pos_middle_35deg_back_X_-210_30_Y_40_open	46.34	51.83	37.74	65.36
Laguna_pos_middle_35deg_back_X_-210_30_Y_80_close	43.45	44.60	36.90	58.60
Laguna_pos_middle_35deg_back_X_-210_30_Y_80_open	39.92	41.23	33.22	52.34
Laguna_pos_middle_35deg_front_X_0_260_Y_-80_close2	42.14	45.64	33.90	55.70
Laguna_pos_middle_35deg_front_X_0_260_Y_-80_open2	37.05	40.92	26.82	49.76

Measurement file name	Attenuation (dB)			
	Mean	Median	Minimum	Maximum
Laguna_pos_middle_35deg_front_X_0_260_Y_-40_close2	39.15	46.00	29.98	69.28
Laguna_pos_middle_35deg_front_X_0_260_Y_-40_open2	39.80	45.02	30.28	69.72
Laguna_pos_middle_35deg_front_X_0_260_Y_0_close2	35.05	43.35	27.70	72.92
Laguna_pos_middle_35deg_front_X_0_260_Y_0_open2	34.30	46.86	25.88	72.60
Laguna_pos_middle_35deg_front_X_0_260_Y_40_close2	40.85	45.35	31.20	70.20
Laguna_pos_middle_35deg_front_X_0_260_Y_40_open2	38.10	43.63	29.06	69.20
Laguna_pos_middle_35deg_front_X_0_260_Y_80_close2	38.14	43.22	28.52	54.92
Laguna_pos_middle_35deg_front_X_0_260_Y_80_open2	36.56	38.68	29.06	64.76
Laguna_pos_middle_35deg_sideL_X_-200_220_Y_-200_close2	43.13	43.82	37.10	50.22
Laguna_pos_middle_35deg_sideL_X_-200_220_Y_-200_open	38.78	40.72	29.86	49.98
Laguna_pos_middle_35deg_sideR_X_-200_220_Y_200_close	45.06	46.58	37.08	53.24
Laguna_pos_middle_35deg_sideR_X_-200_220_Y_200_open	40.43	41.58	31.02	52.24
Laguna_pos_middle_35deg_sideL_X_0_Y_-280_0_close	42.40	47.25	32.84	64.36
Laguna_pos_middle_35deg_sideL_X_0_Y_-280_0_open	40.33	43.28	30.02	65.20
Laguna_pos_middle_35deg_sideR_X_0_Y_0_280_close	38.21	49.68	23.42	70.52
Laguna_pos_middle_35deg_sideR_X_0_Y_0_280_open	36.02	44.40	21.34	67.36
Car with metallic roof, sensor position side left (2)				
Laguna_pos_sideL_35deg_back_X_-240_0_Y_-80_close	51.72	55.40	35.28	61.40
Laguna_pos_sideL_35deg_back_X_-240_0_Y_-80_open	46.69	50.07	38.50	71.04
Laguna_pos_sideL_35deg_back_X_-240_0_Y_-40_close	52.12	58.53	40.50	72.96
Laguna_pos_sideL_35deg_back_X_-240_0_Y_-40_open	52.01	56.30	35.52	73.28
Laguna_pos_sideL_35deg_back_X_-240_0_Y_0_closed	46.93	58.09	38.40	69.76
Laguna_pos_sideL_35deg_back_X_-240_0_Y_0_open	50.30	54.93	35.10	69.08
Laguna_pos_sideL_35deg_back_X_-240_0_Y_40_closed	47.76	53.62	34.20	63.64
Laguna_pos_sideL_35deg_back_X_-240_0_Y_40_open	44.29	53.07	32.54	64.48
Laguna_pos_sideL_35deg_back_X_-240_0_Y_80_close	43.31	46.31	32.84	61.96
Laguna_pos_sideL_35deg_back_X_-240_0_Y_80_open	42.81	48.62	32.72	57.76

Measurement file name	Attenuation (dB)			
	Mean	Median	Minimum	Maximum
Laguna_pos_sideL_35deg_front_X_0_260_Y_-80_close	44.58	48.25	34.10	70.52
Laguna_pos_sideL_35deg_front_X_0_260_Y_-80_open	45.31	48.93	33.62	64.04
Laguna_pos_sideL_35deg_front_X_0_260_Y_-40_close	47.31	52.82	38.78	72.64
Laguna_pos_sideL_35deg_front_X_0_260_Y_-40_open	43.05	55.99	33.22	72.80
Laguna_pos_sideL_35deg_front_X_0_260_Y_0_close	45.69	55.21	35.34	69.76
Laguna_pos_sideL_35deg_front_X_0_260_Y_0_open	48.01	52.20	39.66	68.92
Laguna_pos_sideL_35deg_front_X_0_260_Y_40_close	46.66	52.68	37.18	64.32
Laguna_pos_sideL_35deg_front_X_0_260_Y_40_open	42.01	54.47	32.16	64.48
Laguna_pos_sideL_35deg_front_X_0_260_Y_80_close	42.61	43.22	35.32	63.02
Laguna_pos_sideL_35deg_front_X_0_260_Y_80_open	41.47	43.44	33.02	56.68
Laguna_pos_sideL_35deg_sideL_X_-200_220_Y_-200_close	43.07	44.92	32.16	54.56
Laguna_pos_sideL_35deg_sideL_X_-200_220_Y_-200_open	39.28	41.96	30.16	54.38
Laguna_pos_sideL_35deg_sideR_X_-200_220_Y_200_closed	42.23	43.58	35.22	50.38
Laguna_pos_sideL_35deg_sideR_X_-200_220_Y_200_open	38.25	40.03	29.28	50.56
Laguna_pos_sideL_35deg_sideL_X_0_Y_-280_0_close	43.63	53.56	30.20	66.84
Laguna_pos_sideL_35deg_sideL_X_0_Y_-280_0_open2	40.82	46.51	28.00	68.48
Laguna_pos_sideL_35deg_sideR_X_0_Y_0_280_closed	43.96	45.24	35.02	66.68
Laguna_pos_sideL_35deg_sideR_X_0_Y_0_280_open	33.44	47.12	22.48	67.48

A1.4.4 Summary of all measurement results with 0° angle

Table 38: Summary of measurement results with 0° angle

Measurement file name	Attenuation (dB)			
	Mean	Median	Minimum	Maximum
Laguna_pos_back_0deg_back_X_-200_Y_-200_200_close	46.31	48.62	37.90	56.72
Laguna_pos_back_0deg_back_X_-200_Y_-200_200_open	42.92	45.82	33.72	54.40
Laguna_pos_back_0deg_front_X_220_Y_-200_200_close	29.29	37.12	17.72	50.02
Laguna_pos_back_0deg_front_X_220_Y_-200_200_open	30.64	34.62	18.72	49.04
Laguna_pos_back_0deg_sideL_X_-200_220_Y_-200_close	38.00	42.46	28.28	54.68

Measurement file name	Attenuation (dB)			
	Mean	Median	Minimum	Maximum
Laguna_pos_back_0deg_sideL_X_-200_220_Y_-200_open	36.27	37.92	29.34	54.78
Laguna_pos_back_0deg_sideR_X_-200_220_Y_200_close	41.11	44.46	31.26	55.40
Laguna_pos_back_0deg_sideR_X_-200_220_Y_200_open	37.46	39.22	29.22	54.78
Laguna_pos_middle_0deg_back_X_-200_Y_-200_200_close	42.08	44.84	31.92	52.62
Laguna_pos_middle_0deg_back_X_-200_Y_-200_200_open	40.28	42.36	32.60	50.90
Laguna_pos_middle_0deg_front_X_200_Y_-200_200_close	42.14	43.94	34.18	53.06
Laguna_pos_middle_0deg_front_X_200_Y_-200_200_open	41.29	42.70	34.12	51.30
Laguna_pos_middle_0deg_sideL_X_-200_220_Y_-200_close	37.72	44.10	26.46	52.98
Laguna_pos_middle_0deg_sideL_X_-200_220_Y_-200_open	33.97	40.52	22.46	50.20
Laguna_pos_middle_0deg_sideR_X_-200_220_Y_200_close	41.54	45.36	31.46	52.96
Laguna_pos_middle_0deg_sideR_X_-200_220_Y_200_open	35.72	40.78	25.58	50.20
Laguna_pos_sideL_0deg_back_X_-200_Y_-200_200_close	42.78	44.46	33.56	55.1
Laguna_pos_sideL_0deg_back_X_-200_Y_-200_200_open	39.72	41.62	29.56	53.02
Laguna_pos_sideL_0deg_front_X_220_Y_-200_200_close	39.76	41.38	32.40	53.42
Laguna_pos_sideL_0deg_front_X_220_Y_-200_200_open	38.11	39.66	28.24	52.74
Laguna_pos_sideL_0deg_sideL_X_-200_220_Y_-200_close	43.05	45.98	33.10	55.54
Laguna_pos_sideL_0deg_sideL_X_-200_220_Y_-200_open	37.90	42.44	27.16	56.38
Laguna_pos_sideL_0deg_sideR_X_-200_220_Y_200_close2	37.34	43.04	25.76	51.76
Laguna_pos_sideL_0deg_sideR_X_-200_220_Y_200_open2	31.94	37.56	17.76	50.40

A1.5 ATTENUATION VALUES FOR USE IN SHARING AND COMPATIBILITY STUDIES

The values proposed to be used in sharing and compatibility studies for single entry and aggregated case are collected in Table 39.

The values for the single entry were defined as the minimum value of all measurements. The minimum values for all measurements can be found in Table 36, Table 37 and Table 38 for angle 90°, 35° and 0° respectively. The single entry case is seen as worst-case scenario. In this case the lowest car exit-lost should be considered. To note is that exit-loss for a statistically close scenario may be much higher.

The value for aggregated studies was estimated as a linear mean of all minimum values for single measurements that are listed in Table 36 Table 37 and Table 38 for angles 90°, 35° and 0° accordingly. The aggregated study is seen as a combination of all possible scenarios with various positioning of the car equipped with in-cabin radar, integration inside the cabin (see section 3.2) of in-cabin radars and position of studied service receivers. It was decided to use linear mean value instead of median as it provided more stringent value.

Table 39: Attenuation values to be used in sharing and compatibility studies

Case \ Angle	90°	35°	0°
Single entry study	27 dB	15 dB	18 dB
Aggregated study	33 dB	27 dB	25 dB

ANNEX 2: DUTY CYCLE

A2.1 DEFINITIONS

- Duty Cycle: the ratio, expressed as a percentage, of $\Sigma(T_{on})/(T_{obs})$ where T_{on} is the "on" time of a single transmitter device and T_{obs} is the observation period (see ETSI TS 103 060 [16]);
- T_{dis}: disregard time, i.e. time interval below which interruptions within a transmission are considered part of T_{on} (disregard time) (see ETSI TS 103 060). This is mainly important for pulsed based UWB signals with pulse repetition frequency (PRF) of 1 MHz or higher. This value will be specified in the related harmonised standard;
- T_{obs}: observation period, i.e. reference interval of time (see ETSI TS 103 060).

  For UWB signals there are several observation periods specified, e.g. 1 second, 1 minute or 1 hour (depending on the applicable regulation) or based on the "signal repetition time" (T_{rep}) or during TX_{on} Signal repetition time is specified as: TX_{on} + TX_{off} (see for example Figure 77 and Figure 78)
- P_{thresh}: power level above which the signal is detected as "on".

Based on T_{on} and T_{off} of the transmitting signal, the duty cycle is calculated as:

$$Duty\ Cycle = \frac{\sum TX_{on}}{T_{obs}} = \frac{\sum TX_{on}}{\sum TX_{on} + \sum TX_{off}} \qquad (7)$$

Where:

- T_{obs}, T_{dis} and P_{thresh} are defined in ETSI TS 103 060 and as specified in the relevant harmonised standard.

The power limits specified in this Report for the automotive radars are during the TX_{on} time. A Duty Cycle requirement would reduce the interfering power by

$$DC[dB] = 10 \times \log\left(DC[\%]/100\right) \qquad (8)$$

A2.2 EXAMPLE FOR FREQUENCY MODULATED SIGNAL

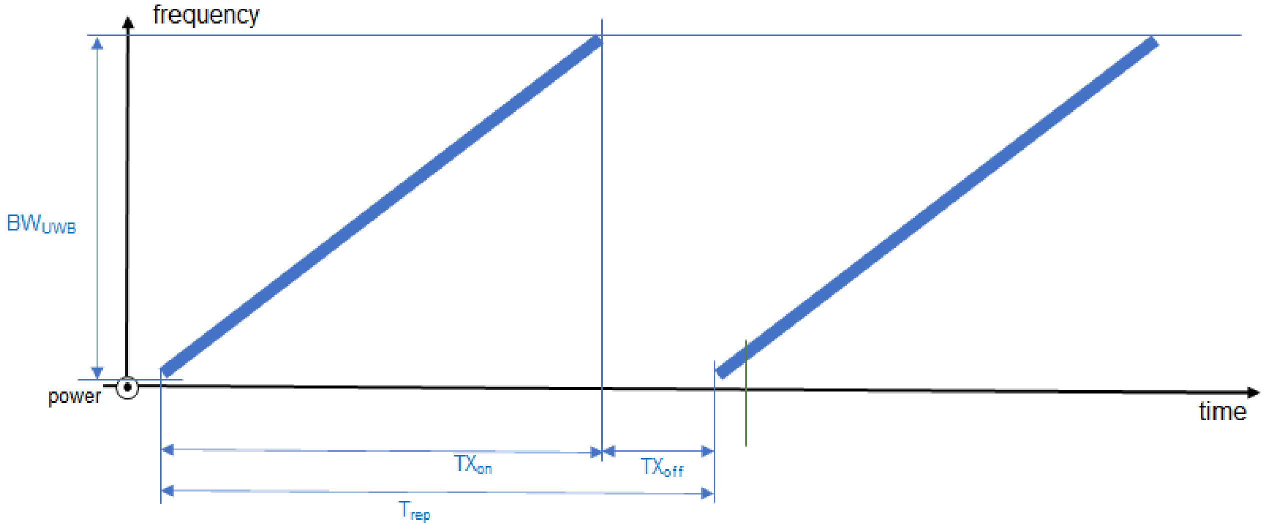


Figure 77: DC consideration for an FMCW modulated signal; frequency over time

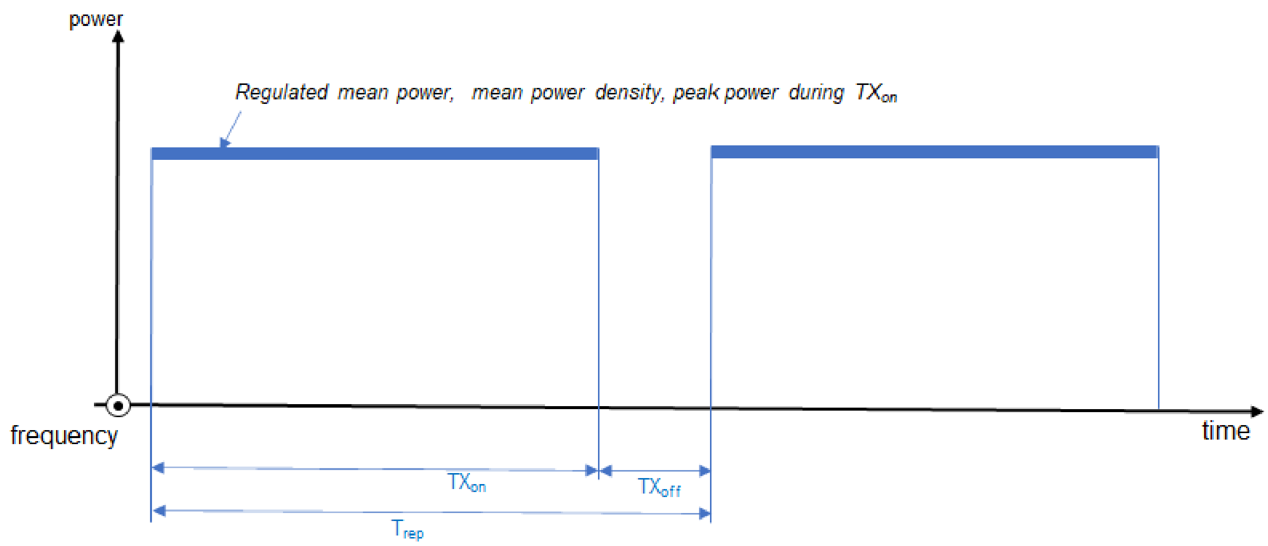


Figure 78: DC consideration for an FMCW modulated signal; power over time

Duty Cycle consideration for:

- One modulation sweep during TX_{on};
- T_{dis} < TX_{off}.

Duty Cycle in general

$$DC = \frac{\sum TX_{on}}{T_{obs}} = \frac{\sum TX_{on}}{\sum TX_{on} + \sum TX_{off}} \tag{9}$$

If T_{obs} specified as T_{rep}, this simplifies to

$$DC_{via\,T_{rep}} = \frac{TX_{on}}{T_{rep}} \tag{10}$$

A2.3 EXAMPLE FOR PULSE BASED MODULATED SIGNAL

Simplified for T_{dis}>T_{rep} (high PRF)

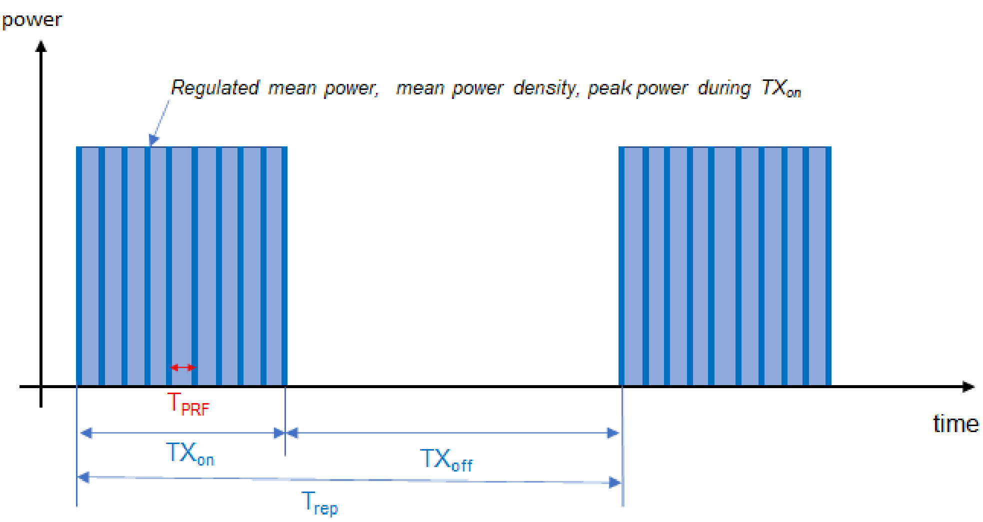


Figure 79: DC consideration for a pulsed based modulated signal (high PRF); Power over time

$$\mathrm{DC} = \frac{\sum \mathrm{TX_{on}}}{\mathrm{T_{obs}}} = \frac{\sum \mathrm{TX_{on}}}{\sum \mathrm{TX_{on}} + \sum \mathrm{TX_{off}}} \tag{11}$$

Simplified for T_{dis}<T_{rep} (low PRF)

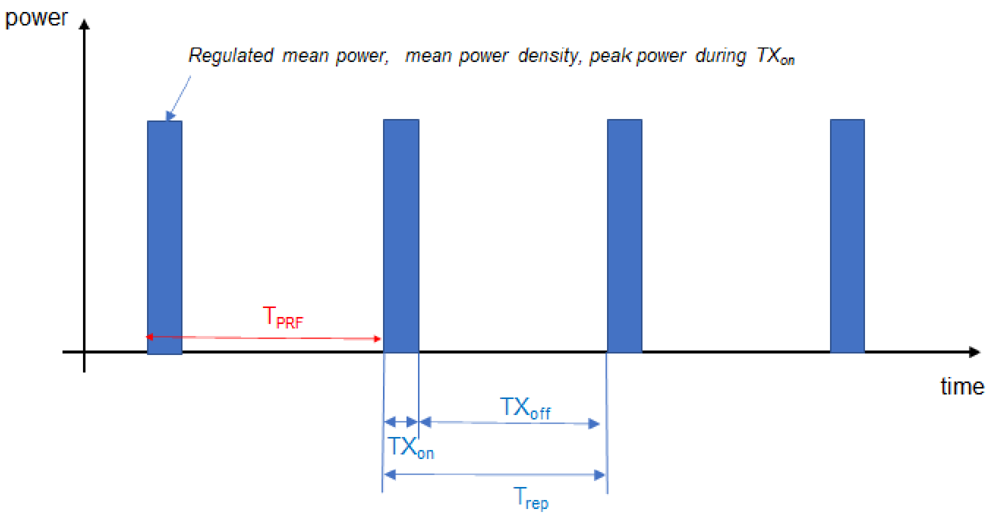


Figure 80: DC consideration for a pulsed based modulated signal (low PRF); power over time

$$\mathrm{DC} = \frac{\sum \mathrm{TX_{on}}}{\mathrm{T_{obs}}} = \frac{\sum \mathrm{TX_{on}}}{\sum \mathrm{TX_{on}} + \sum \mathrm{TX_{off}}} \tag{12}$$

ANNEX 3: RAS COORDINATION ZONES

This annex contains detailed investigation, methodology and results for sharing and compatibility studies between exterior vehicular radars and Radio Astronomy Service.

A3.1 INTRODUCTION

This annex further analyses the results obtained from the sharing and compatibility study with RAS summarised in section 3.5. In particular, it provides analysis whether the areas created by the zero-margin lines overlap with roads, then a methodology for defining coordination zones.

Figure 16 and Figure 17from section 3.5 provide a view of the zero-margin contour lines for the two example frequencies of 120 and 140 GHz, for the NOEMA and IRAM RAS site respectively. It can be seen that for both sites, the rightmost figures, for 140 GHz, yield more and larger zero-margin contour lines. Thus, the rest of the analysis will be focusing on 140 GHz frequency, as a more stringent use case to meet.

A3.2 NOEMA ANALYSIS

A3.2.1 Situational analysis for the 9.0 dBm/8 GHz zero-margin lines

Roads have been added to the display of Figure 16 from section 3.5, with a zoom in the vicinity of the NOEMA RAS, the leading to Figure 81. It can be seen that several areas of the map include zero-margin contour lines for 9.0 dBm/8 GHz (orange lines). These areas of interest are numbered for further analysis. In Figure 81, the white circles in the figures mark distances from the RAS station in steps of 10 kilometres.

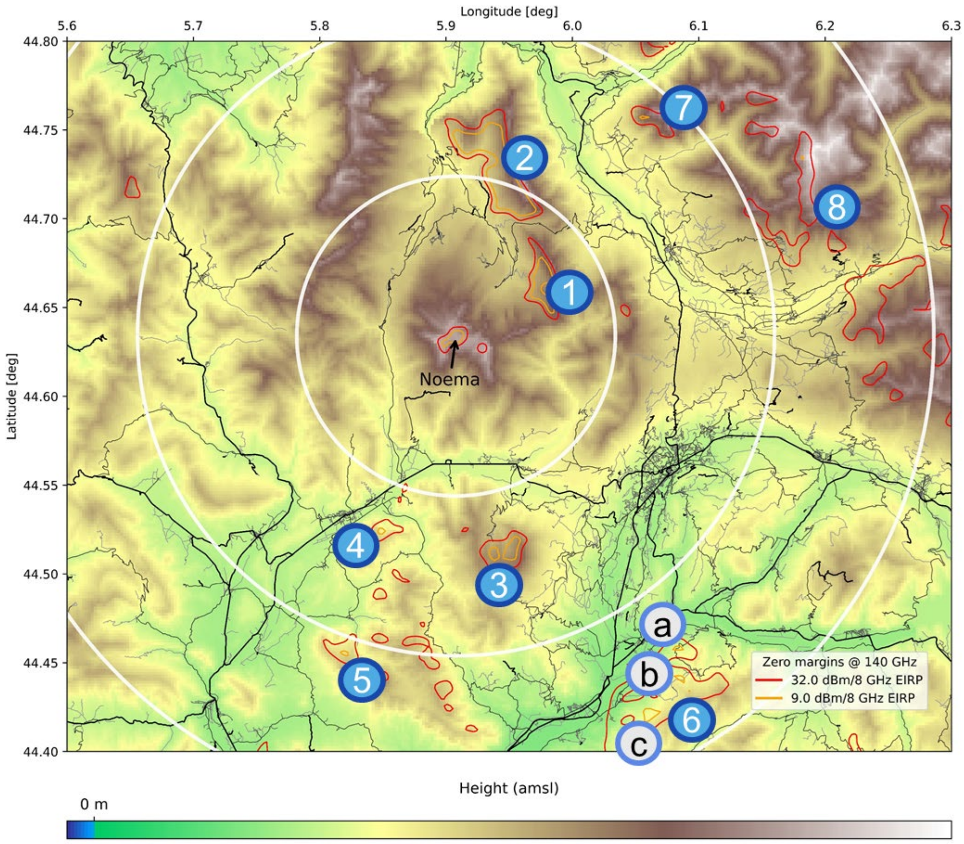


Figure 81: Regions of zero-margin around the NOEMA site for different e.i.r.p. values at 140 GHz, with roads (zoom around NOEMA)

Analysis of these areas of interest is summarised in Table 40.

Table 40: Areas of interest for NOEMA and their situation

Area number	Situation for: 9 dBm/8 GHz (orange lines)
1	Areas created by zero-margin lines do not cross any roads. Mountain ridge.
2	Areas created by zero-margin lines do not cross any roads. Mountain ridge.
3	Areas created by zero-margin lines do not cross any roads. Mountain ridge.
4	Areas created by zero-margin lines do not cross any roads. Mountain ridge.
5	Areas created by zero-margin lines do not cross any roads. Mountain ridge.
6(a)	Small sections of narrow mountain road near the village of Venterol. Large parts of these sections have dense clutter (forest).
6(b)	
6(c)	Areas created by zero-margin lines do not cross any roads.
7	Areas created by zero-margin lines do not cross any roads. Mountain ridge.
8	Areas created by zero-margin lines do not cross any roads. Mountain ridge.

It is concluded that that only areas 6(a) and 6(b) need further study, as the other areas of interest to not happen to cross any roads (being mountain ridges).

Figure 82 provides yet a more zoomed view in the vicinity of area of interest #6. Areas 6(a) and 6(b) are relatively short sections of narrow mountain road near the village of Venterol.

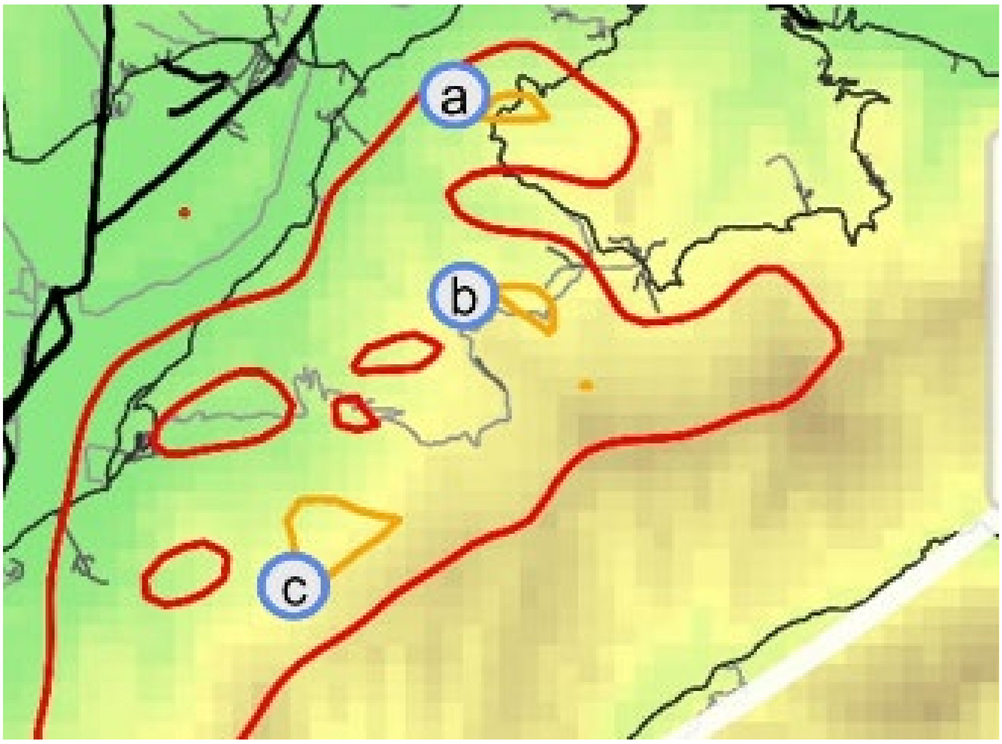


Figure 82: Regions of zero-margin around the NOEMA site for different e.i.r.p. values at 140 GHz, with roads, further zoom on area of interest #6

Figure 83 and Figure 84 provide satellite views [31] of areas 6(a) and 6(b), respectively.

Figure 83: Satellite view of area of interest 6(a)

Figure 84: Satellite view of area of interest 6(b)

It can be seen from Figure 83 and Figure 84 that on large parts of these road sections, there is dense clutter (forest) on both sides of the road. Only one very limited spot in 6(a) is not shielded by clutter in direction of the RAS. Area 6(b) looks well shielded.

Therefore, it is concluded that only 2 road sections can be found inside the areas circled by the 9 dBm/8 GHz (orange) zero-margin lines. These two road sections are narrow mountain roads with dense clutter (forest).

Thus, it is concluded that 9 dBm/8 GHz (orange lines) can be considered as an acceptable power level. No risk of interference to Noema RAS site is foreseen for corner and short/ultra-short exterior vehicular radars under such conditions.

A3.2.2 Situational analysis for the 32.0 dBm/8 GHz zero-margin lines

Figure 85 provides complementary views to Figure 17 showing the map slightly zoomed, without terrain (leftmost plot), with terrain (middle plot) and with roads (rightmost plot). Names of relevant localities have also been added and can also be consulted in Table 41.

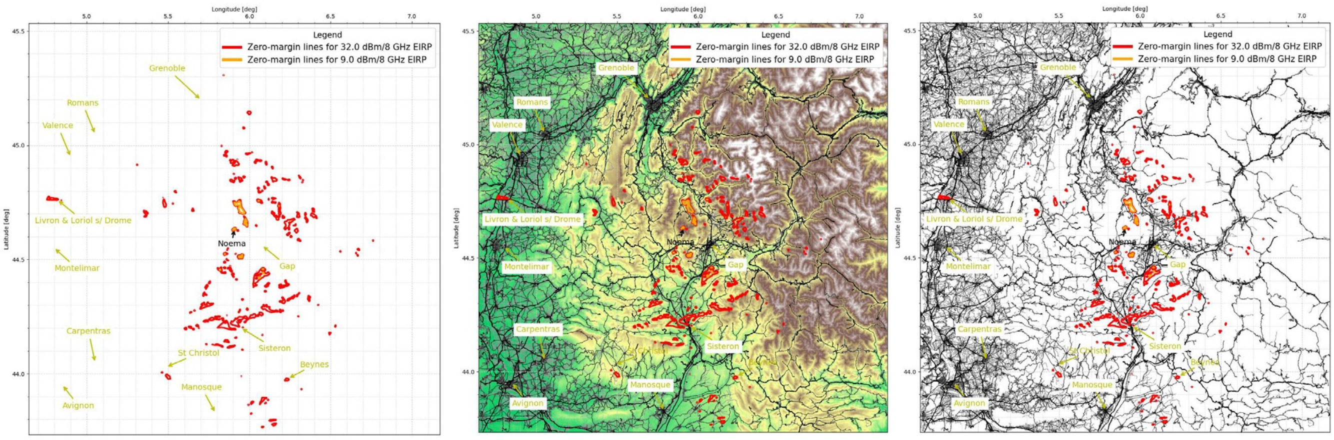


Figure 85: Regions of zero-margin around the NOEMA site for different e.i.r.p. , without terrain nor roads, with terrain, and with roads

Table 41: Number of inhabitants in metropolitan areas nearby NOEMA

Metropolitan area name	Number of inhabitants [31]
Grenoble	689840
Valence	181814
Montélimar	79087
Gap	63849
Sisteron	17205

It can be seen from Figure 85 that the situation for the 32.0 dBm/8 GHz zero-margin lines (red) is different than the situation for the 9.0 dBm/8 GHz zero-margin lines (orange). They are distributed over a wider area, and they do happen to overlap with urban areas and roads.

Figure 86 provides a categorisation of the areas of interest stemming from the 32 dBm/8 GHz zero-margin lines:

- The blue dotted lines circles highlight the risk-of-interference places, where the areas inside the red zero-margin lines do cross some roads;
- The green dotted lines circles highlight the not-risk-of-interference places, where the areas inside the red zero-margin lines do not cross any roads (thus having some zero-margin lines in such places is not a problem; this may happen for example on the top of a mountain ridge);
- The yellow dotted lines circles highlight the immediate vicinity of the RAS.

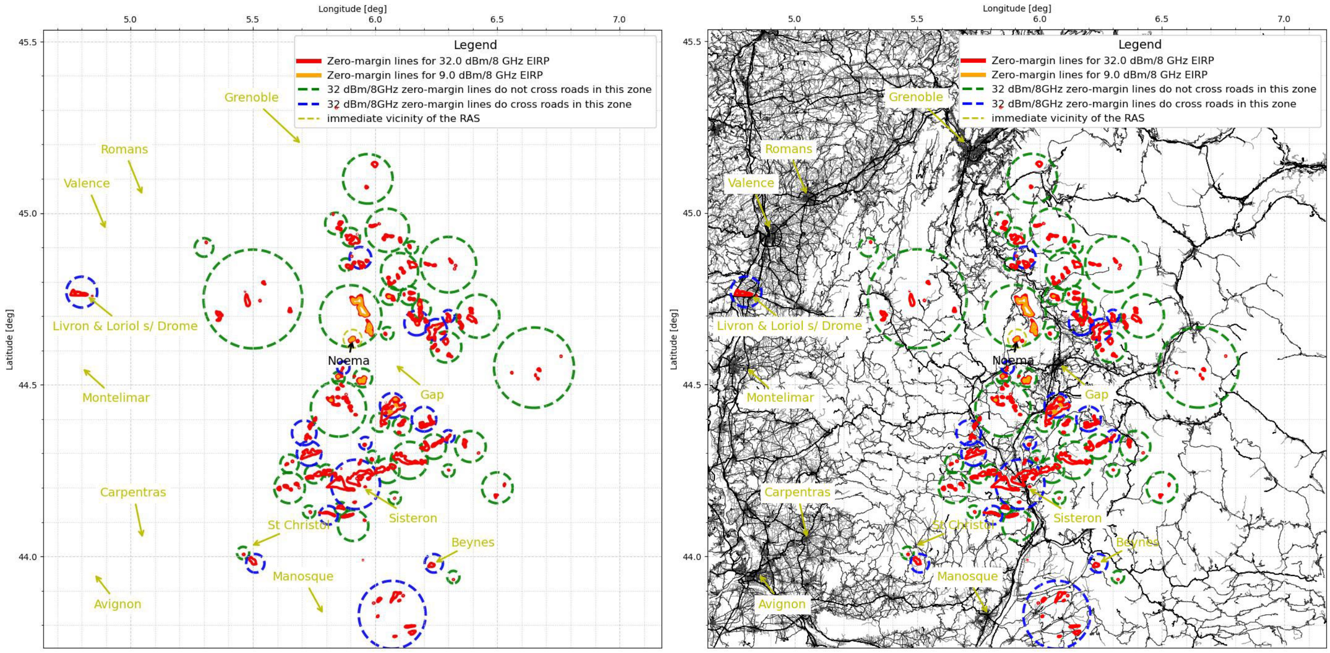


Figure 86: Regions of zero-margin around the NOEMA site for different e.i.r.p., with crude categorisation of the 32 dBm/8 GHz areas of interest

It can be seen from Figure 86 that the risk-of-interference areas are rather remote from each other (could be referred to as clusters), and they do not form a continuous area. An example of such situation is the cluster near Livron and Loriol sur Drome, which is rather small and quite distant from the other ones.

A3.2.3 Immediate Vicinity of the RAS and associated exclusion zone

Radio telescope community indicated the need to protect the immediate vicinity (3 km radius around the RAS) of both telescopes with a very stringent power limit (ideally a switch-off), since it is possible that people would drive cars up to the telescope even in absence of roads or bring cars up to the RAS using cable car.

Figure 87 provides a zoom of the rightmost plot of Figure 86. The yellow dotted lines circles highlight the immediate vicinity of the RAS, with a radius of 3 km. Even if no roads are present in that area, it needs to be protected.

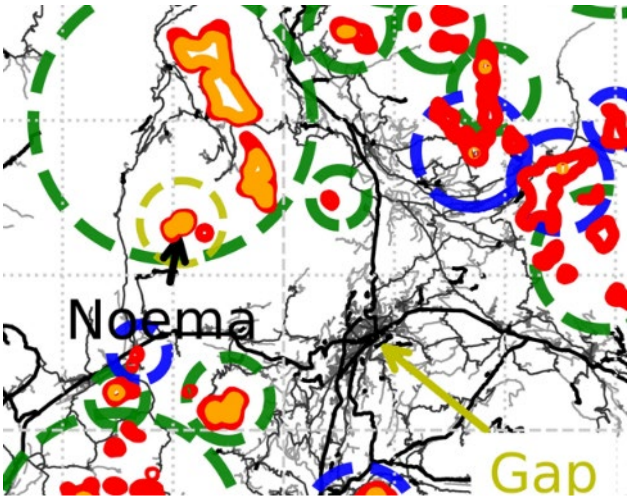


Figure 87: NOEMA, zoom on RAS immediate vicinity

Thus, to ensure protection of the immediate vicinity of the RAS, one exclusion zone is defined with radius of 3 km centred on the RAS.

Table 42: NOEMA, Exclusion zone details

Exclusion zone number	LON	LAT	Radius (km)
#1	5.907917	44.633889	3

A3.2.4 Coordination zones design

A3.2.4.1 Option 1

Option 1 defines one coordination zone, centred on the RAS, that is very large. The maximum power level limitation within this zone is quite severe (driven by the risk-of-interference areas in close vicinity of the RAS), and such zone does include large metropolitan areas (e.g. Grenoble and Valence) or important highways (e.g. A7). The coordination zone(s) details are provided in Table 43.

Table 43: NOEMA, coordination zones details, option 1

Coordination zone number	LON	LAT	Radius (km)	Max.pow (dBm/8 GHz)
#1	5.907917	44.633889	100	9

Figure 88 provides a detailed view of this option, showing that all the risk-of-interference areas (within the blue dotted line circles) are well within coordination zone(s).

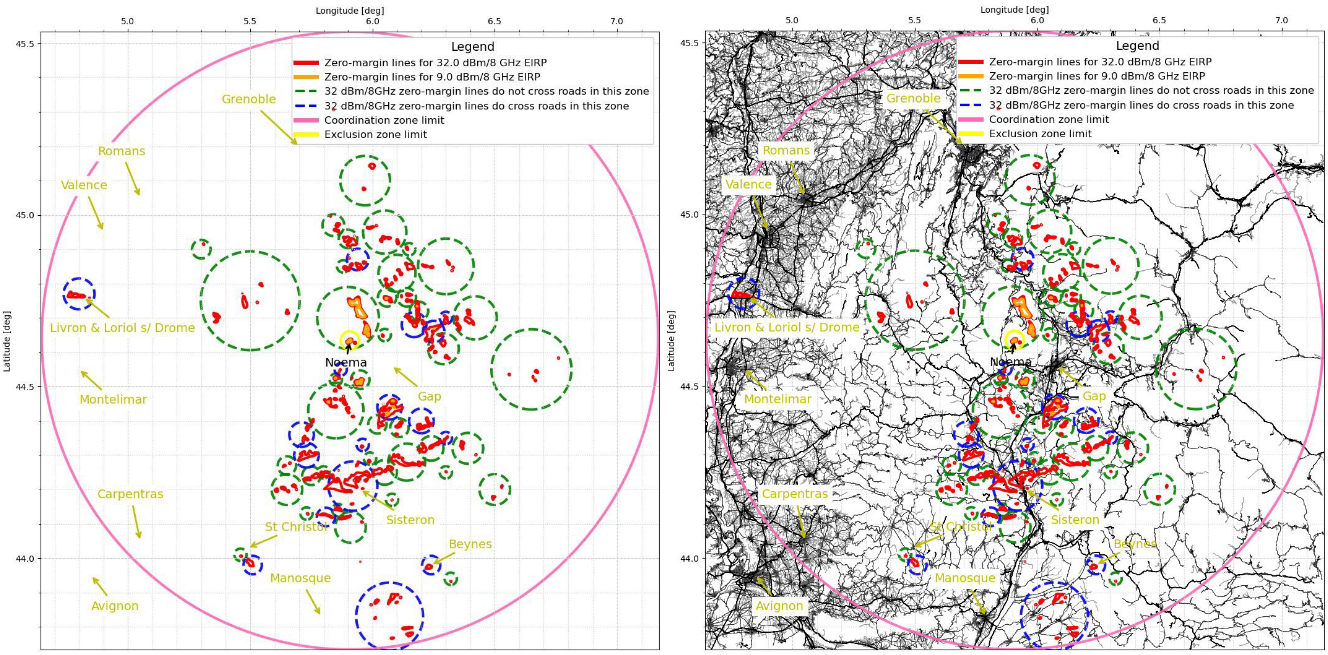


Figure 88: NOEMA, coordination zone details, option 1, display with and without roads

Figure 89 provides a summary view of this option, where the coordination zone(s) area(s) is colour-filled.

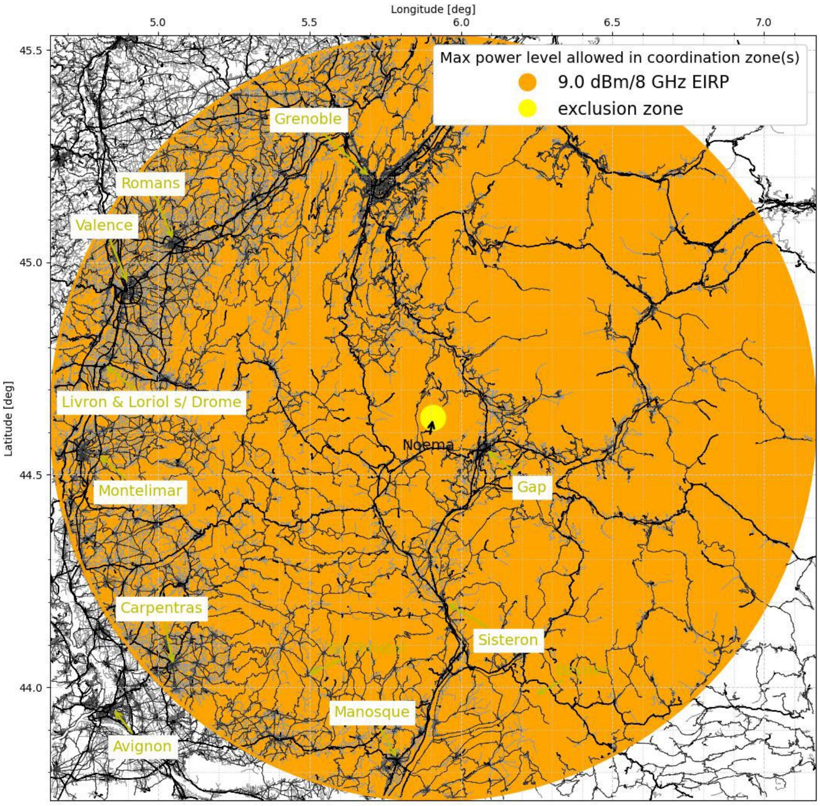


Figure 89: NOEMA, coordination zone summary, option 1

A3.2.4.2 Option 2

Option 2 defines five coordination zones. This allows to remove some large metropolitan areas (e.g. Grenoble, Valence) or important highways (e.g. A7) from coordination zones, but it still includes Gap and Sisteron. The coordination zone(s) details are provided in Table 44.

Table 44: NOEMA, coordination zones details, option 2

Coordination zone number	LON	LAT	Radius (km)	Max.pow (dBm/8 GHz)
#1	5.88	44.49	45	9
#2	4.80	44.77	6	29
#3	6.24	43.98	4	25
#4	5.51	43.98	4	25
#5	6.07	43.83	12	27

Figure 90 provides a detailed view of this option, showing that all the risk-of-interference areas (within the blue dotted line circles) are well within coordination zone(s).

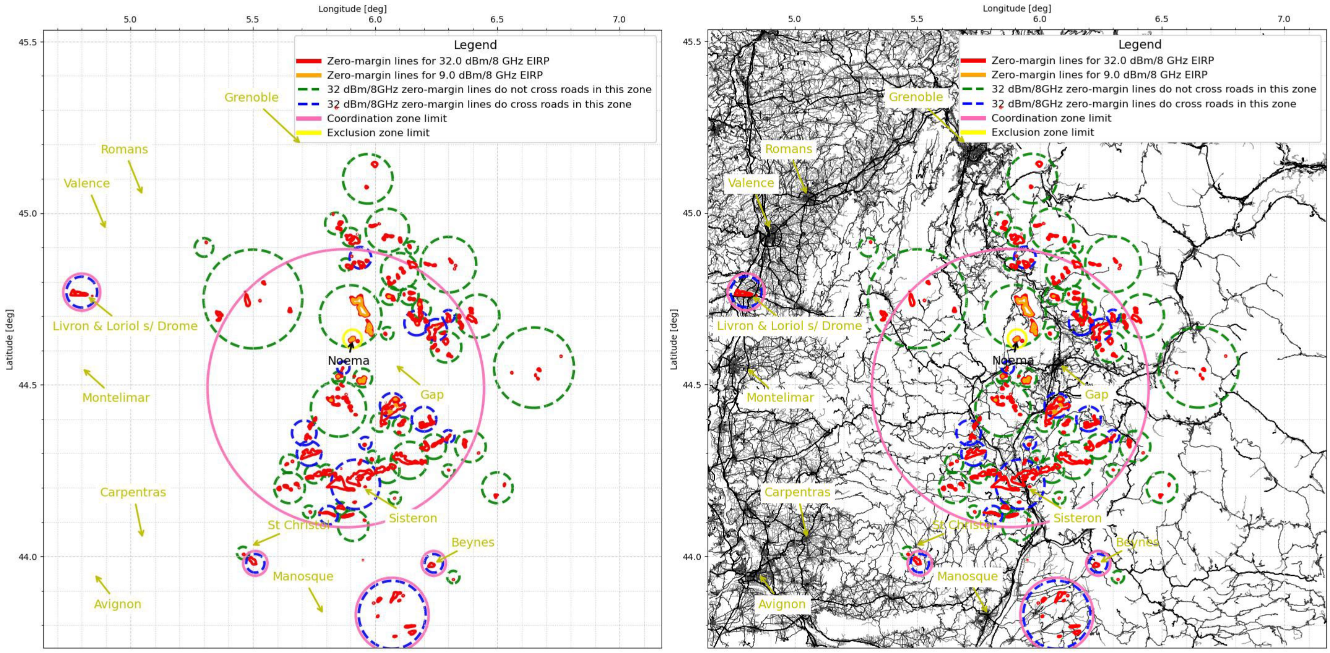


Figure 90: NOEMA, coordination zone details, option 2, display with and without roads

Figure 91 provides a summary view of this option, where the coordination zone(s) area(s) is colour-filled.

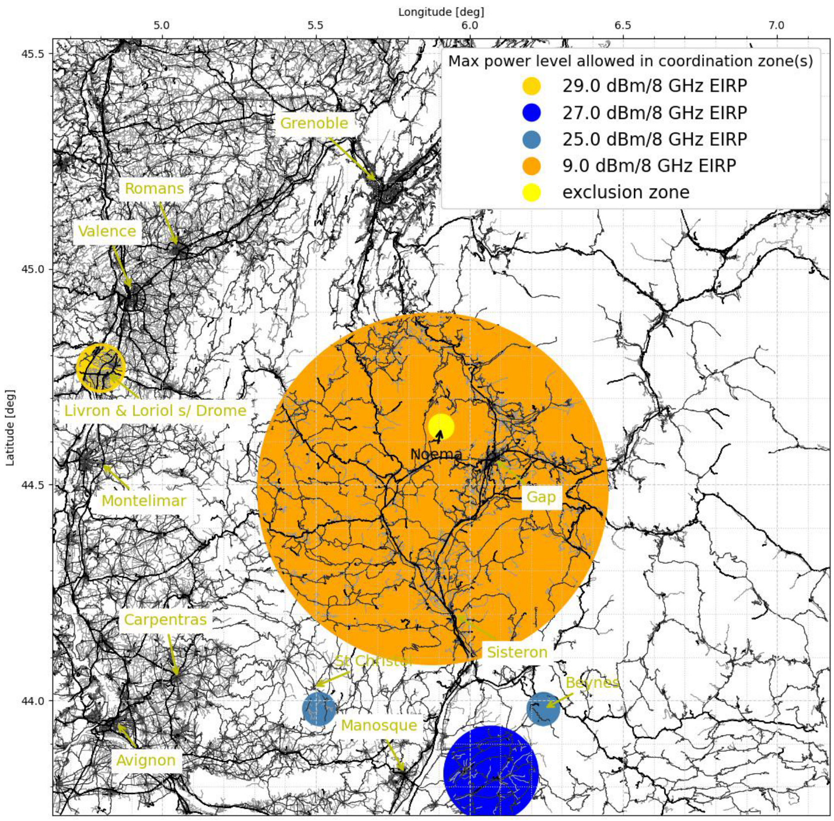


Figure 91: NOEMA, coordination zone summary, option 2

A3.2.4.3 Option 3

Option 3 defines ten coordination zones. This allows to remove some large metropolitan areas (e.g. Grenoble, Valence, Gap) or important highways (e.g. A7) from coordination zones, but it still includes Sisteron. The coordination zone(s) details are provided in Table 45.

Table 45: NOEMA, coordination zones details, option 3

Coordination zone number	LON	LAT	Radius (km)	Max.pow (dBm/8 GHz)
#1	4.80	44.77	6	29
#2	6.24	43.98	4	25
#3	5.51	43.98	4	25
#4	6.07	43.83	12	27
#5	6.23	44.68	9	9
#6	5.94	44.87	4.5	14
#7	5.87	44.55	3	26
#8	6.13	44.40	10	9
#9	6.30	44.35	3	24
#10	5.80	44.25	19	14

Figure 92 provides a detailed view of this option, showing that all the risk-of-interference areas (within the blue dotted line circles) are well within coordination zone(s).

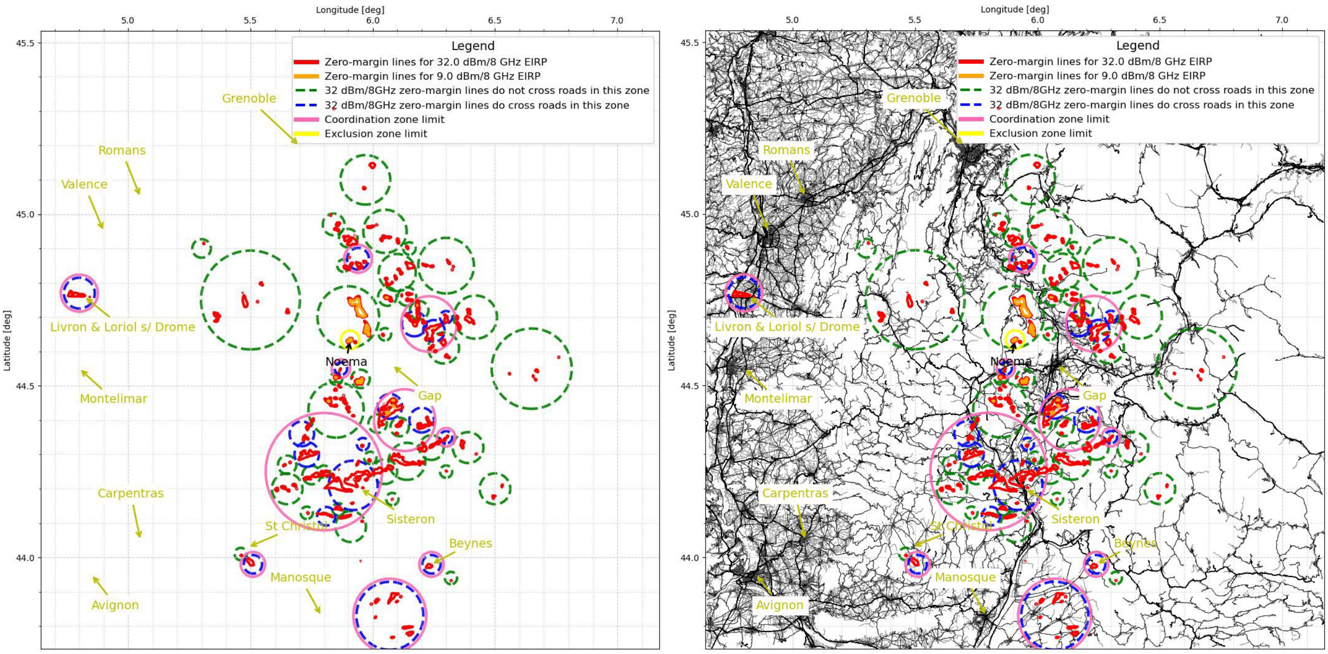


Figure 92: NOEMA, coordination zone details, option 3, display with and without roads

Figure 93 provides a summary view of this option, where the coordination zone(s) area(s) is colour-filled.

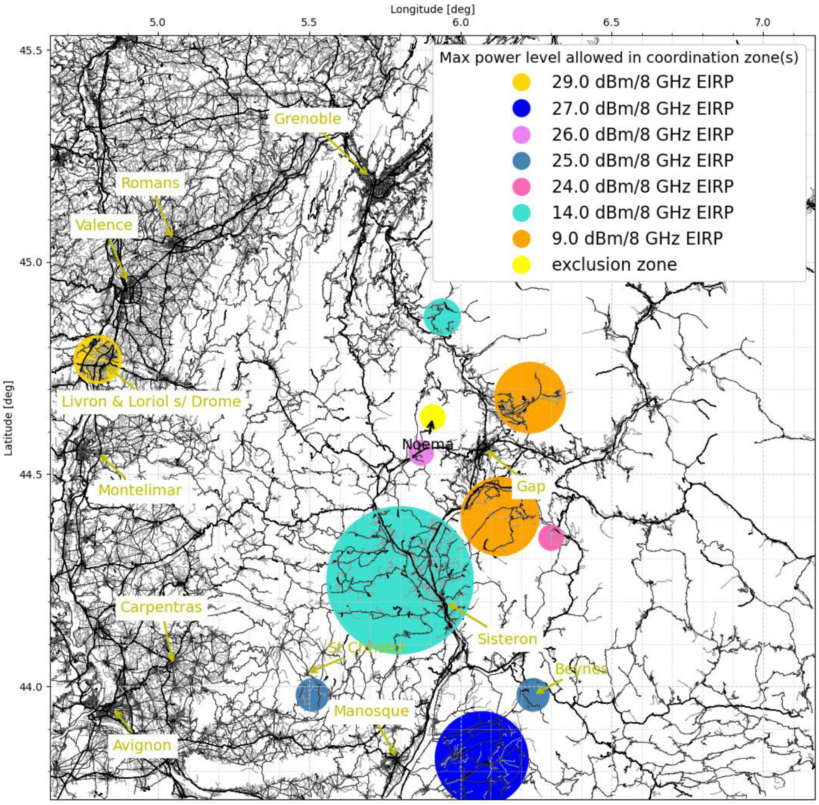


Figure 93: NOEMA, coordination zone summary, option 3

A3.2.4.4 Option 4

Option 4 is an intermediate between Option 2 and Option 3. It defines ten coordination zones as Option 3, which allows to remove some large metropolitan areas (e.g. Grenoble, Valence and Gap) or important highways (e.g. A7) from coordination zones, but it still includes Sisteron. The coordination zone(s) details are provided in Table 46. Compared to option 3, option 4 has fewer entries for the maximum power levels (coarser granularity, like in Option 2).

Table 46: NOEMA, coordination zones details, option 4

Coordination zone number	LON	LAT	Radius (km)	Max.pow (dBm/8 GHz)
#1	4.80	44.77	6	29
#2	6.24	43.98	4	24
#3	5.51	43.98	4	24
#4	6.07	43.83	12	27
#5	6.23	44.68	9	9
#6	5.94	44.87	4.5	9
#7	5.87	44.55	3	26
#8	6.13	44.40	10	9
#9	6.30	44.35	3	24
#10	5.80	44.25	19	9

Figure 94 provides a detailed view of this option, showing that all the risk-of-interference areas (within the blue dotted line circles) are well within coordination zone(s).

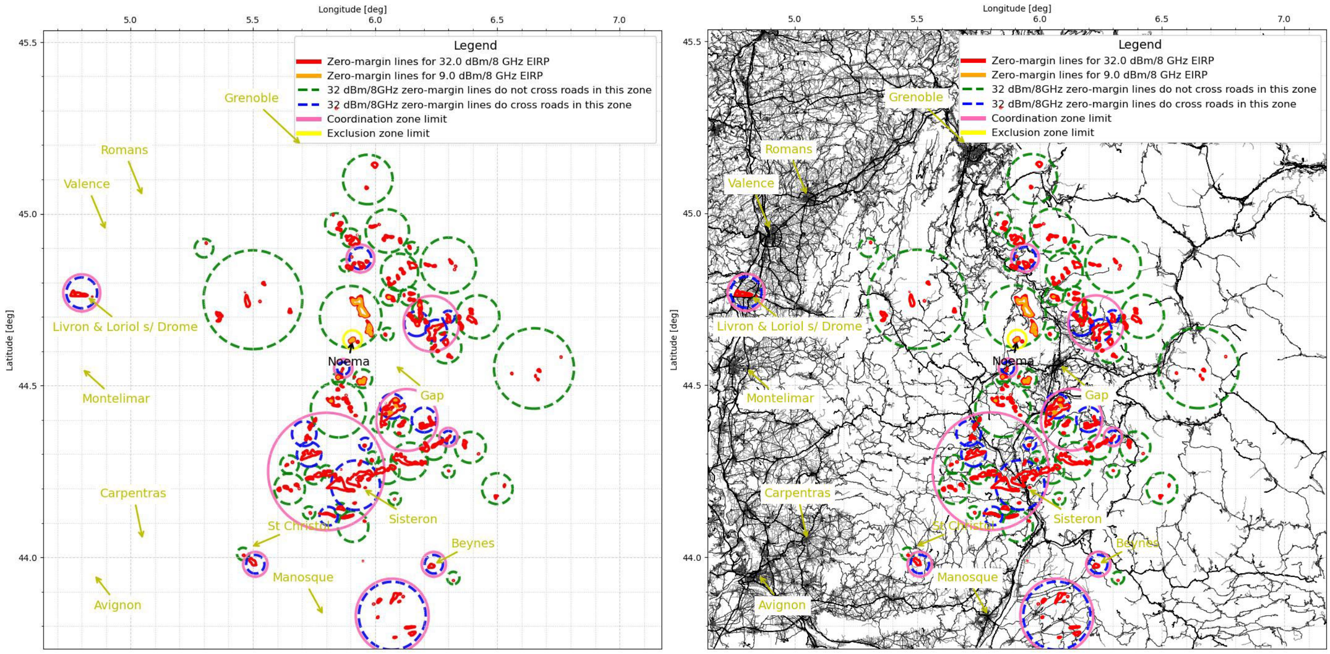


Figure 94: NOEMA, coordination zone details, option 4, display with and without roads

Figure 95 provides a summary view of this option, where the coordination zone(s) area(s) is colour-filled.

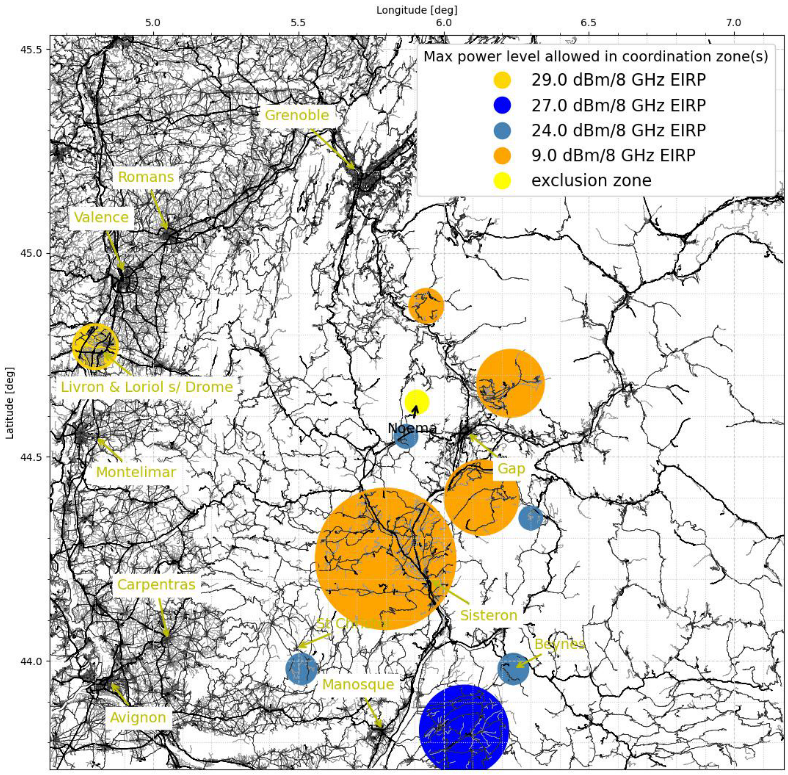


Figure 95: NOEMA, coordination zone summary, option 4

A3.2.4.5 Comparison of design options

Larger number of coordination zones allows to have a finer granularity and thereby reduce the overall area impacted, as shown by Table 47, although with increased complexity (both definition and testing).

Table 47: NOEMA, coordination zones options and impacts

Option	Number of coordination zones	Area with Max.power constraints for short/corner radars	Area with Max.power constraints for front radars
Option 1	1	0 km²	31416 km²
Option 2	5	0 km²	7028 km²
Option 3	10	0 km²	2489 km²
Option 4	10	0 km²	2489 km²

A3.3 IRAM ANALYSIS

A3.3.1 Situational analysis for the 9.0 dBm/8 GHz zero-margin lines

Continuing the analysis from Figure 17, terrain colouring has been removed, additional power levels of 6 and -6 dBm/8 GHz have been added, and map is shown with or without roads, leading to Figure 96. From that figure, it can be seen that several areas of the map include zero-margin contour lines for 9.0 dBm/8 GHz (orange lines), but it can also be seen that zero-margin contour lines for 6.0 dBm/8 GHz (blue lines) are only present in the vicinity of the IRAM telescope.

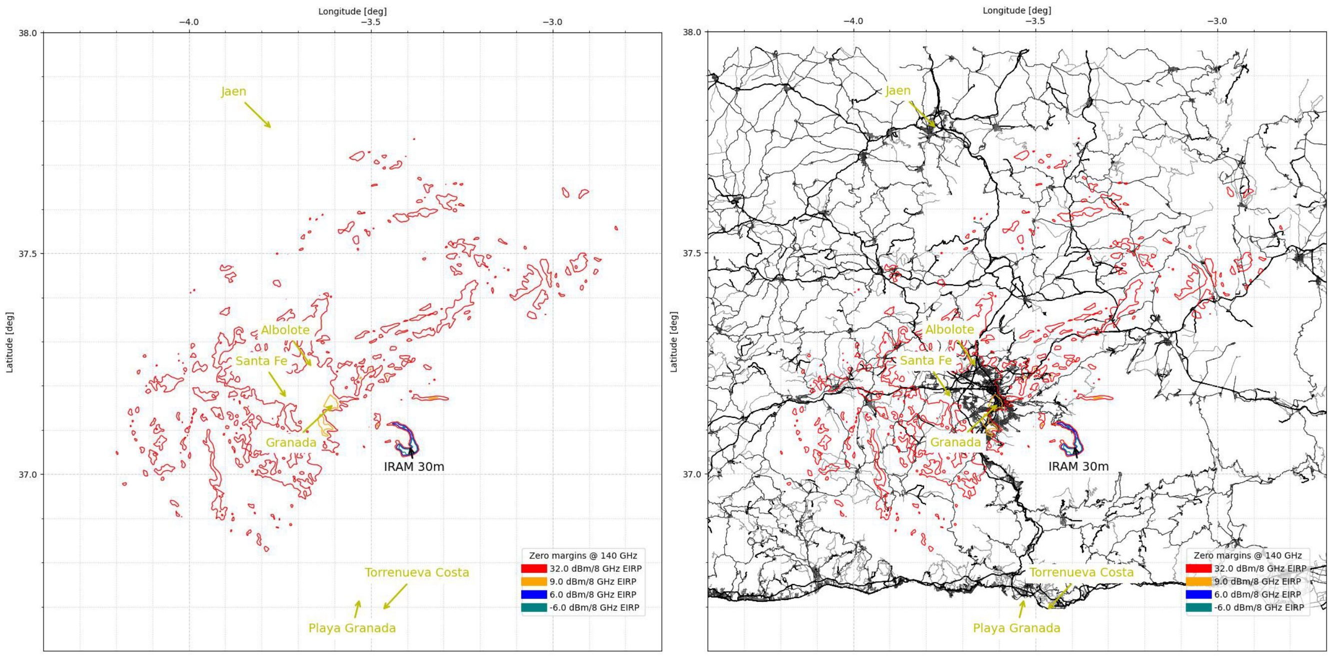


Figure 96: Regions of zero-margin around the IRAM site for different e.i.r.p. values at 140 GHz, with roads, with and without roads

Figure 97 provides a categorisation of the areas of interest stemming from the 9 dBm/8 GHz zero-margin lines:

- The grey dotted lines circles highlight the risk-of-interference places, where the areas inside the red zero-margin lines do cross some roads;
- The green dotted lines circles highlight the not-risk-of-interference places, where the areas inside the red zero-margin lines do not cross any roads (thus having some zero-margin lines in such places is not a problem; this may happen for example on the top of a mountain ridge);
- The yellow dotted lines circles highlight the immediate vicinity of the RAS.

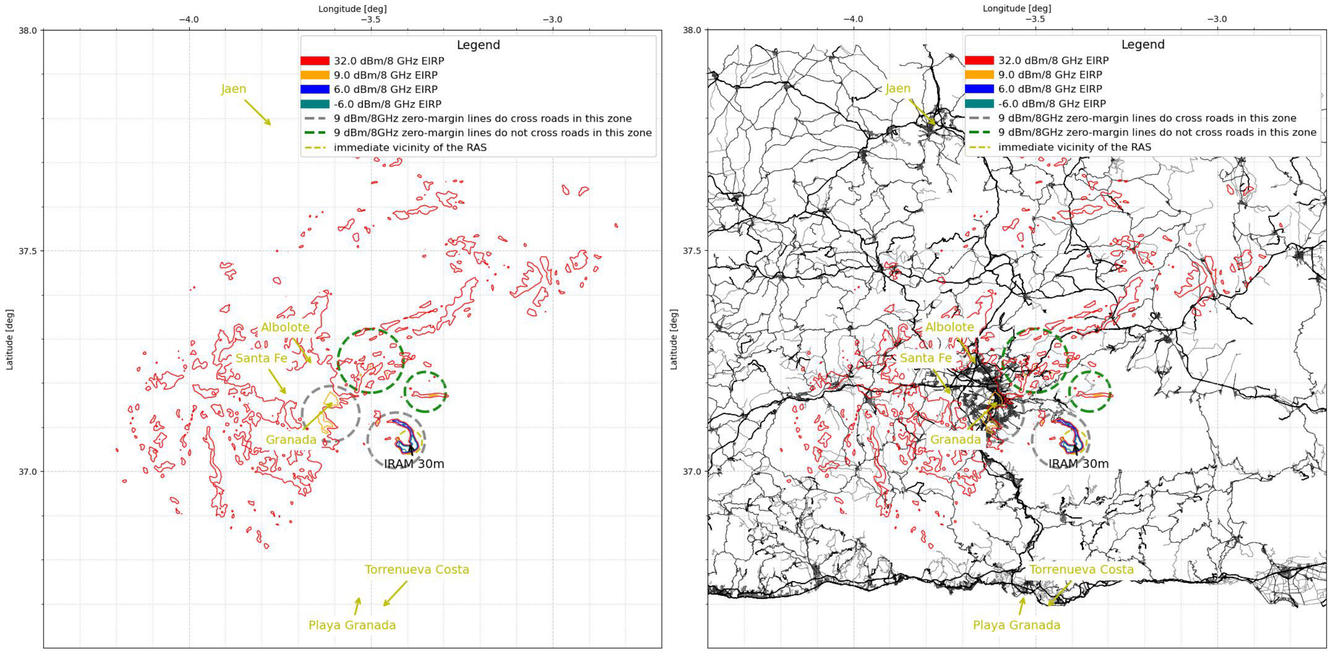


Figure 97: Regions of zero-margin around the IRAM site for different e.i.r.p., with crude categorisation of the 9 dBm/8 GHz areas of interest

It can be seen from Figure 97 that there are only two risk-of-interference areas: the east side of Granada city and the vicinity of IRAM. Also, it can be observed that the zero-margin contour lines for 6.0 dBm/8 GHz (blue lines) are only present in the vicinity of the IRAM telescope, thus arguably solving the issue for the city of Granada.

Figure 98 provides a zoom of the situation in the vicinity of IRAM telescope. It appears that the zone within the blue contour lines includes a ski resort area (e.g. with hotels and parkings etc.). It can also be seen that the zone within the teal contour lines (-6 dBm/8 GHz) reduced to only one area of interest which includes 2 roads with dense clutter.

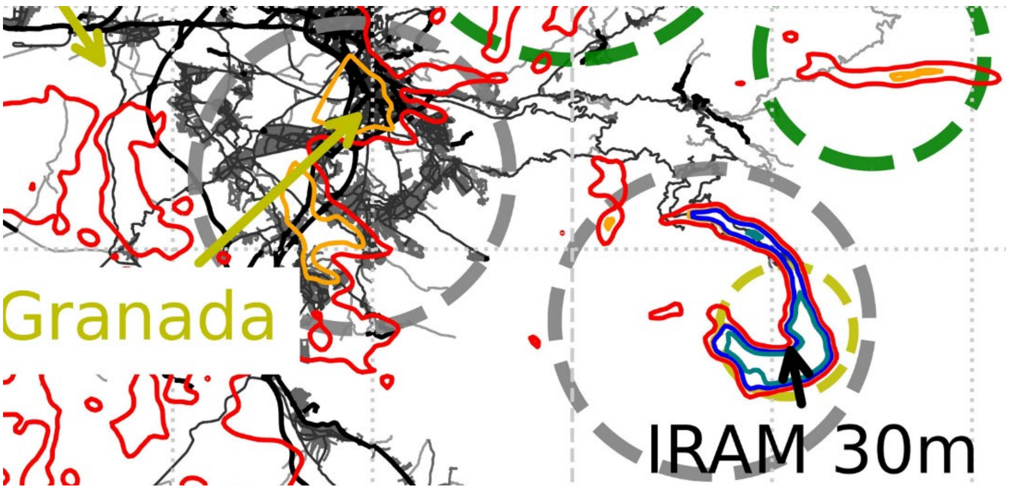


Figure 98: Regions of zero-margin around the IRAM site for different e.i.r.p. values at 140 GHz, with roads, zoom with annotations

As shown with Figure 99, using a satellite view, it can be seen that the area of interest includes two very small road sections, which have dense clutter (forest) on both sides, arguably shielding any signal in direction of the RAS.

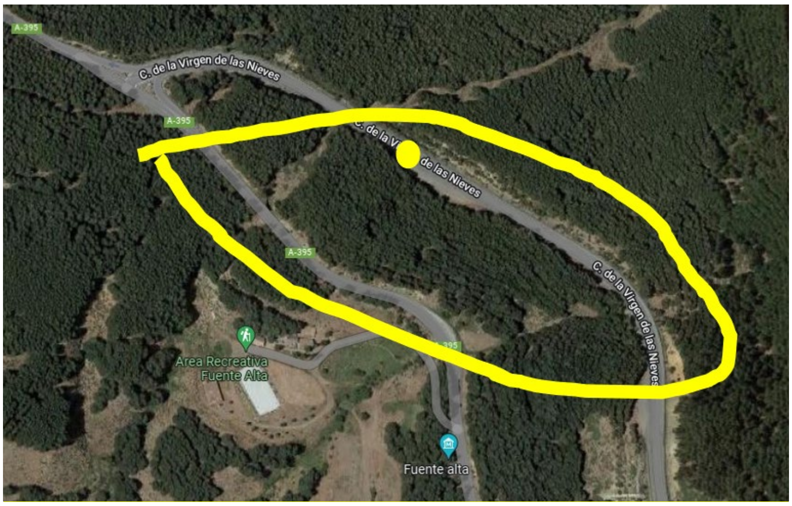


Figure 99: Satellite view of area of interest, roads near IRAM

Street view confirms this impression, as shown with Figure 100 for the location shown with a dot in Figure 99.

Figure 100: Example streetmap view within area of interest

For the IRAM RAS site, the 6 dBm/8 GHz (blue) zero-margin contour lines avoid the city of Granada but not the ski resort next to the RAS site, while the -6 dBm/8 GHz (teal) zero-margin contour lines manage to avoid also the ski resort area, leaving only a very small region of two road sections within the contour lines. These two road sections are narrow mountain road with dense clutter (forest).

Based on this analysis, it is concluded that for the vicinity of the IRAM site, -6 dBm/8 GHz (teal lines) can be considered as an acceptable power level generating no significant interference toward the RAS. No risk of interference to IRAM RAS site is foreseen for corner and short/ultra-short exterior vehicular radars under such conditions.

A3.3.2 Situational analysis for the 32.0 dBm/8 GHz zero-margin lines

It can be seen from Figure 97 that the situation for the 32.0 dBm/8 GHz zero-margin lines (red) is different than the situation for the 9.0 dBm/8 GHz zero-margin lines (orange). They are distributed over a wider area, and they do happen to overlap with urban areas and roads. A detailed investigation as done for 9 dBm/8 GHZ power level does not appear reasonable.

Names of relevant localities have also been added and can also be consulted in Table 48.

Table 48: number of inhabitants in metropolitan areas nearby IRAM

Metropolitan area name	Number of inhabitants [31]
Granada	498365
Jaen	191652
Costa Tropical de Granada	125449

A3.3.2 Immediate Vicinity of the RAS and associated exclusion zone

Radio telescope community indicated the need to protect the immediate vicinity (3 km radius around the RAS) of both telescopes with a very stringent power limit (ideally a switch-off), since it is possible that people would drive cars up to the telescope even in absence of roads or bring cars up to the RAS using cable car.

As it can be seen from Figure 98, The yellow dotted lines circles highlight the immediate vicinity of the RAS, with a radius of 3 km. Even if no roads are present in that area, it needs to be protected.

Thus, to ensure protection of the immediate vicinity of the RAS, one exclusion zone is defined with radius of 3 km centred on the RAS.

Table 49: IRAM, Exclusion zone details

Exclusion zone number	LON	LAT	Radius (km)
#1	-3.92778	37.066111	3

A3.3.3 Coordination zones design

A3.3.3.1 Option 1

Option 1 defines a unique and large coordination zone. The maximum power level limitation within this zone is quite severe (driven by the risk-of-interference areas in close vicinity of the RAS), and such zone does include large metropolitan areas (e.g. Granada and Jaen) or important highways (e.g. A-7, A-44 and A-92). The coordination zone(s) details are provided in Table 50.

Table 50: IRAM, coordination zones details, option 1

Coordination zone number	LON	LAT	Radius (km)	Maximum pow (dBm/8 GHz)
#1	-3.52	37.30	70	-6

Figure 101 provides a detailed view of this option, showing that all the risk-of-interference areas (within the grey dotted line circles) are well within coordination zone(s).

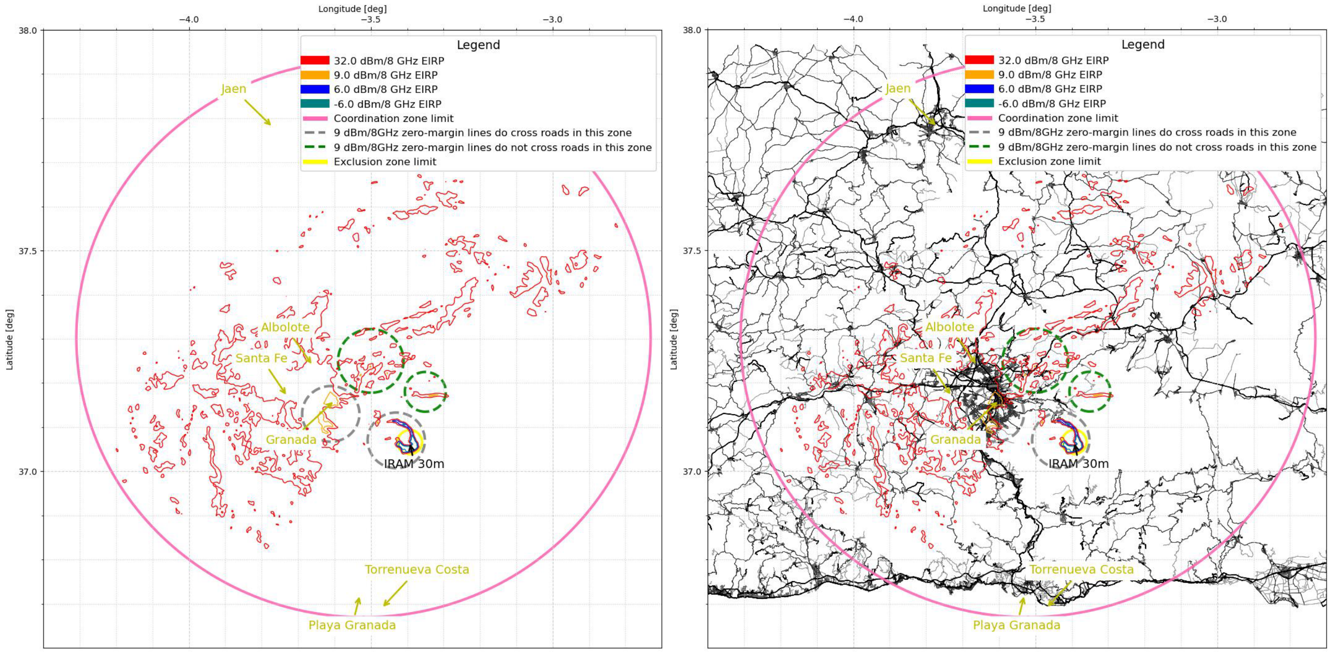


Figure 101: IRAM, coordination zone details, option 1, display with and without roads

Figure 102 provides a summary view of this option, where the coordination zone(s) area(s) is colour-filled.

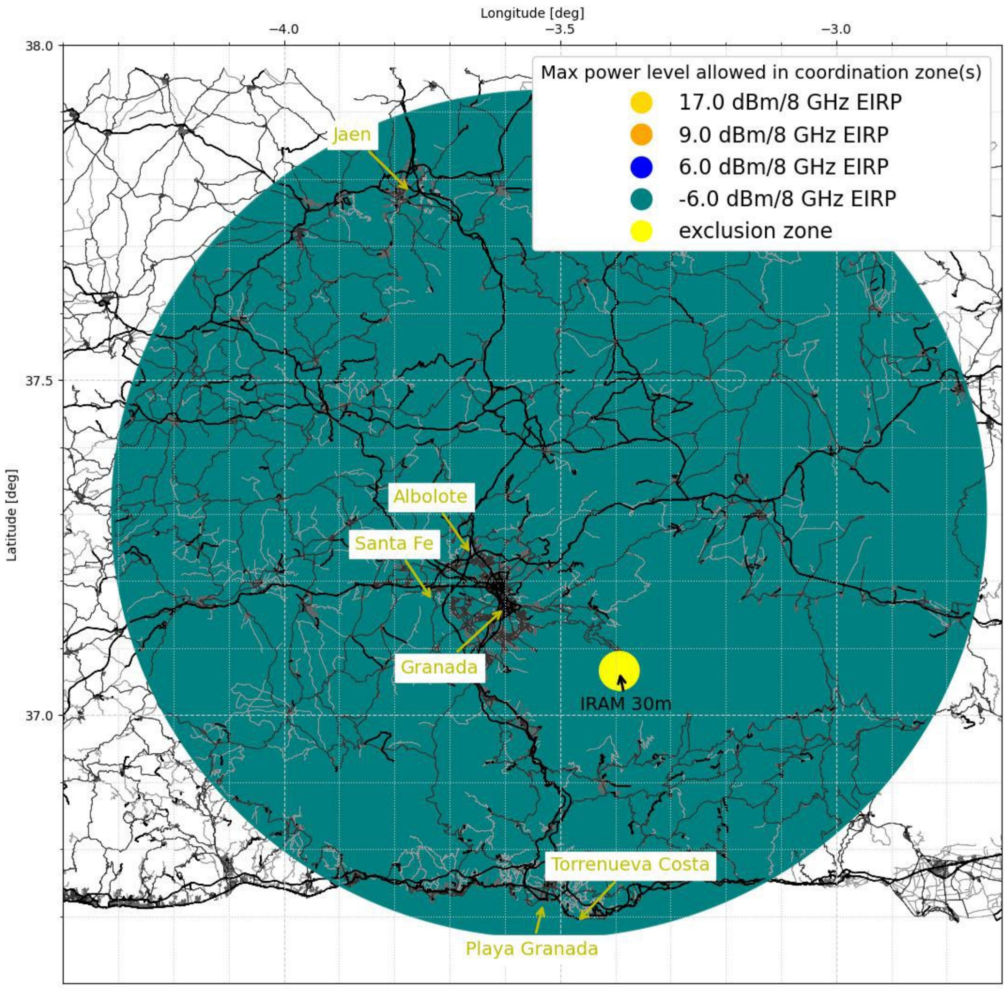


Figure 102: IRAM, coordination zone summary, option 1

A3.3.3.2 Option 2

Option 2 defines three coordination zones. This allows to remove some large metropolitan areas (e.g. Jaen, Costa Tropical de Granada and west part of Granada) or important highways (e.g. A-7, A-92 and A-44) from coordination zones, but it still includes east part of Granada. The east side of Granada has a maximum power level of 6 dBm/8 GHz (3 dB down from corner and short radar power), and the IRAM vicinity a maximum power level of -6 dBm/8 GHz. The coordination zone(s) details are provided in Table 51.

Table 51: IRAM, coordination zones details, option 2

Coordination zone number	LON	LAT	Radius (km)	Max.pow (dBm/8 GHz)
#1	-3.52	37.30	70	9
#2	-3.62	37.13	7	6
#3	-3.92778	37.066111	8	-6

Figure 103 provides a detailed view of this option, showing that all the risk-of-interference areas (within the grey dotted line circles) are well within coordination zone(s).

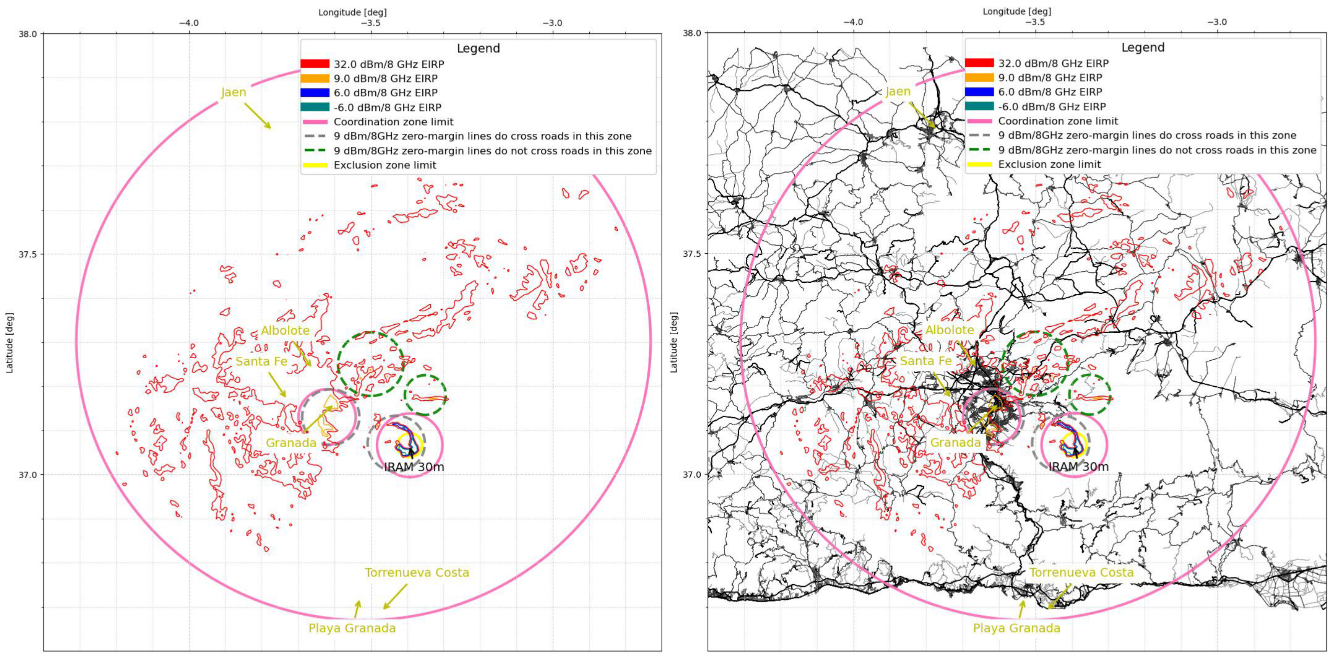


Figure 103: IRAM, coordination zone details, option 2, display with and without roads

Figure 104 provides a summary view of this option, where the coordination zone(s) area(s) is colour-filled.

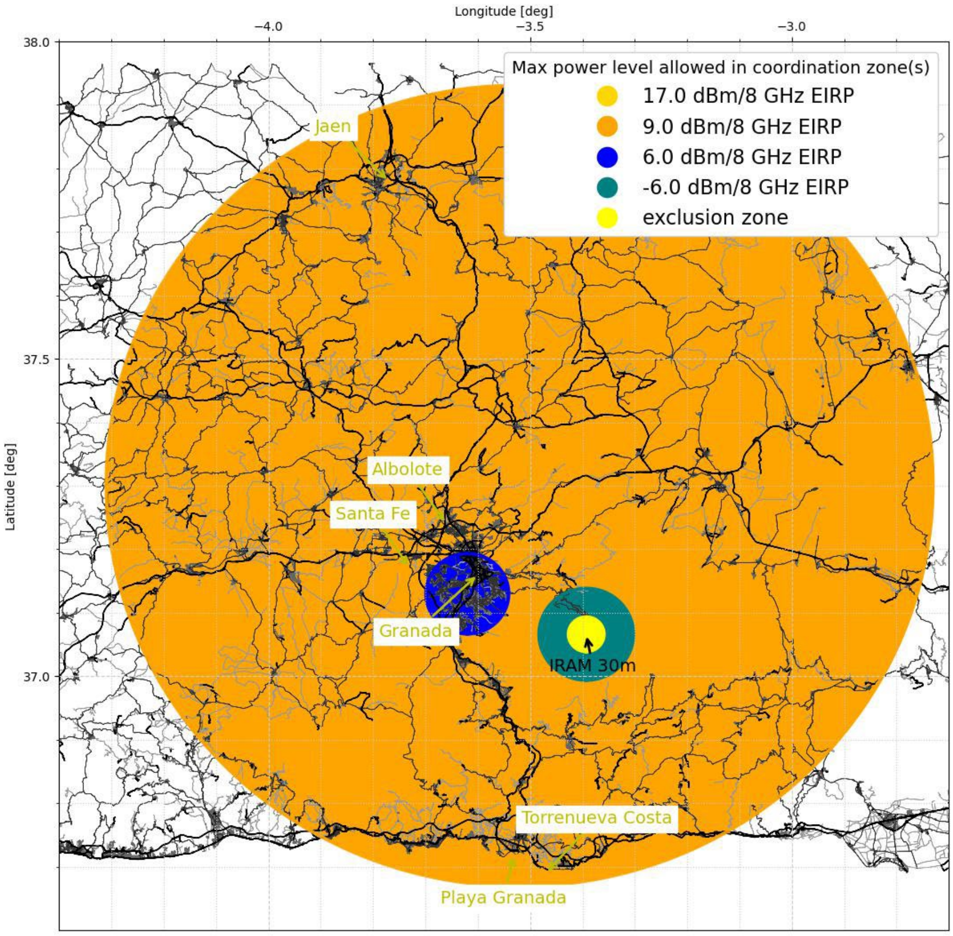


Figure 104: IRAM, coordination zone summary, option 2

A3.3.3.3 Option 3

Option 3 defines four coordination zones. Like option 2, this allows to remove some large metropolitan areas (e.g. Jaen, Costa Tropical de Granada and west part of Granada) or important highways (e.g. A-7, A-92 and A-44) from coordination zones, but it still includes east part of Granada. The major difference compared to option 2, is that an under an intermediate maximum power level limitation of 17 dBm/8 GHz (15 dB down from front radar power) is introduced for the outermost part of the big zone. The west part of Granada and west of A-92, A44 are under the maximum power limitation of 9 dBm/8 GHz (corner and short radar power), while the east side of Granada has a maximum power level of 6 dBm/8 GHz (3 dB down from corner and short radar power), and the IRAM vicinity a maximum power level of -6 dBm/8 GHz. The coordination zone(s) details are provided in Table 52.

Table 52: IRAM, coordination zones details, option 3

Coordination zone number	LON	LAT	Radius (km)	Maximum pow (dBm/8 GHz)
#1	-3.52	37.30	70	17
#2	-3.48	37.18	34	9
#3	-3.62	37.13	7	6
#4	-3.92778	37.066111	8	-6

Figure 105 provides a detailed view of this option, showing that all the risk-of-interference areas (within the grey dotted line circles) are well within coordination zone(s).

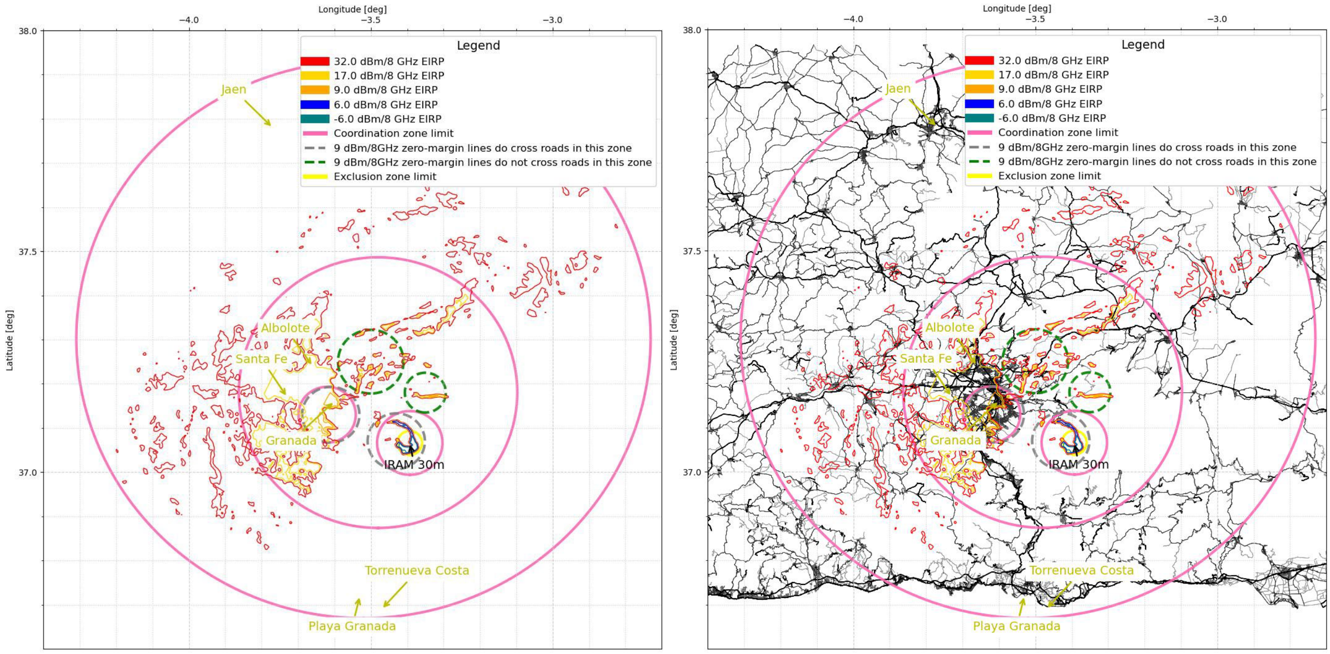


Figure 105: IRAM, coordination zone details, option 3, display with and without roads

Figure 106 provides a summary view of this option, where the coordination zone(s) area(s) is colour-filled.

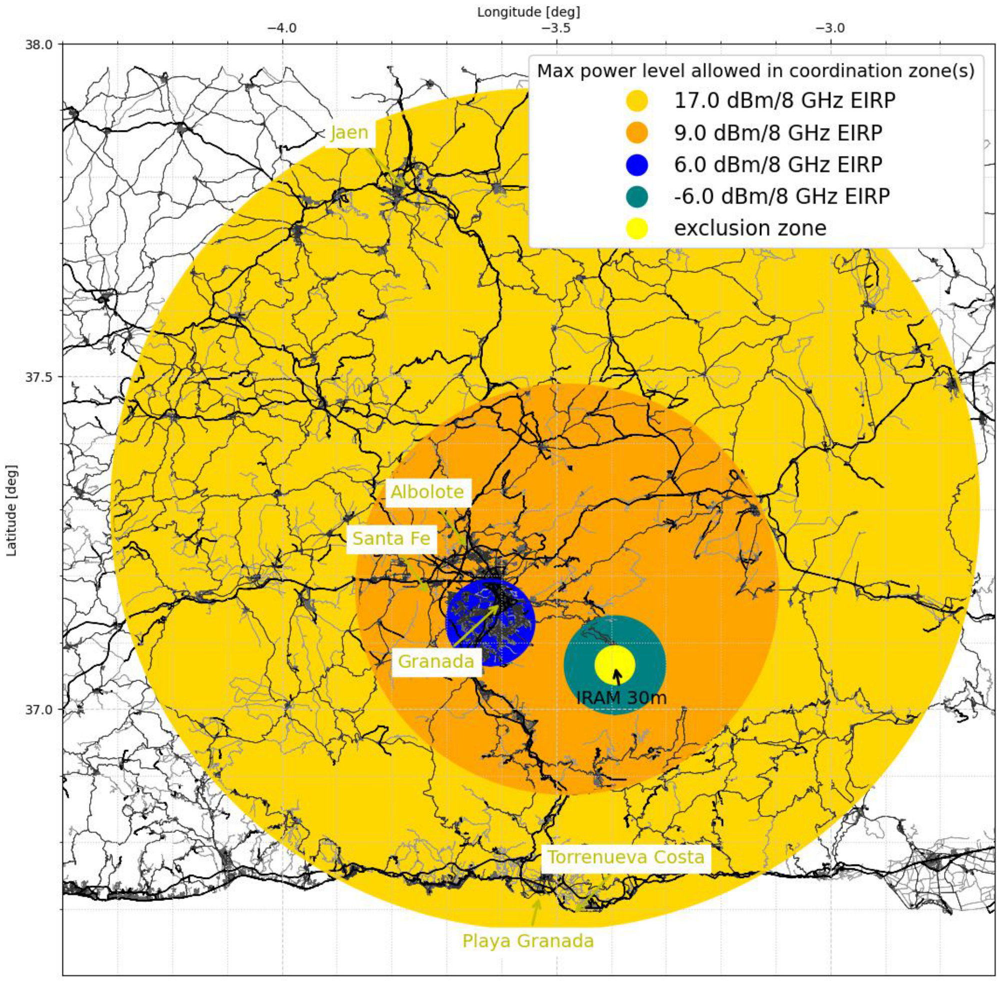


Figure 106: IRAM, coordination zone summary, option 3

A3.3.3.4 Comparison of design options

Larger number of coordination zones allows to have a finer granularity and thereby reduce the overall area impacted, as shown by Table 53, although with increased complexity (both definition and testing).

Table 53: IRAM, coordination zones options and impacts

Option	Number of coordination zones	Area with maximum power constraints for short/corner radars	Area with maximum power constraints for front radars at 25 dBm	Area with maximum power constraints for front radars at 40 dBm
Option 1	1	15394 km²	15394 km²	15394 km²
Option 2	3	355 km²	15394 km²	15394 km²
Option 3	4	355 km²	3632 km²	15394 km²

ANNEX 4: LIST OF REFERENCES

[1] ETSI TR 103 498 "System Reference document (sRdoc); Short Range Devices (SRD) using Ultra Wide Band (UWB); Transmission characteristics; Radiodetermination applications within the frequency range 120 GHz to 260 GHz"

[2] Recommendation ITU-R M.2057: “Systems characteristics of automotive radars operating in the frequency band 76-81 GHz for intelligent transport systems applications”

[3] Recommendation ITU-R P.2108-0: “Prediction of clutter loss”

[4] Recommendation ITU-R P.452-16: “Prediction procedure for the evaluation of interference between stations on the surface of the Earth frequencies above about 0.1 GHz”

[5] Recommendation ITU-R P.676-12: “Attenuation by atmospheric gases and related effects”

[6] Recommendation ITU-R P.835-6: “Reference standard atmospheres”

[7] ECC Report 334 "UWB radiodetermination applications in the frequency range 116-260 GHz", approved January 2022

[8] “Handbook on Radio Astronomy”, Third Edition of 2013, ITU Radiocommunication Bureau

[9] Recommendation ITU-R RA.314-10: “Preferred frequency bands for radio astronomical measurements”

[10] The Cologne Database for Molecular Spectroscopy CDMS https://cdms.astro.uni-koeln.de/

[11] Recommendation ITU-R RA.769-2: “Protection criteria used for radio astronomical measurements”

[12] Atacama Large Millimeter/submillimeter Array (ALMA); https://almascience.eso.org/

[13] Recommendation ITU-R RS.1861: “Typical technical and operational characteristics of Earth exploration-satellite service (passive) systems using allocations between 1.4 and 275 GHz”

[14] Recommendation ITU-R RS.515-5: “Frequency bands and bandwidths used for satellite passive remote sensing”

[15] Recommendation ITU-R RS.2017-0: “Performance and interference criteria for satellite passive remote sensing”

[16] ETSI TS 103 060: "Electromagnetic compatibility and Radio spectrum Matters (ERM); Short Range Devices (SRD); Method for a harmonized definition of Duty Cycle Template (DCT) transmission as a passive mitigation technique used by short range devices and related conformance test methods"

[17] Report ITU-R F.2323-0: “Fixed service use and future trends”

[18] Recommendation ITU-R F.758-7: “System parameters and considerations in the development of criteria for sharing or compatibility between digital fixed wireless systems in the fixed service and systems in other services and other sources of interference”

[19] Report ITU-R F.2416-0: “Technical and operational characteristics and applications of the point-to-point fixed service applications operating in the frequency band 275-450 GHz”

[20] ECC Report 282: “Point-to-point Radio Links in the Frequency Ranges 92−114.25 GHz and 130−174.8 GHz”, approved September 2018

[21] ECC Recommendation (18)01: “Radio frequency channel/block arrangements for “Fixed Service systems operating in the bands 130−148.5 GHz, 151.5−164 GHz and 167−174.8 GHz”, approved April 2018

[22] ECC Recommendation (18)02: “Radio frequency channel/block arrangements for Fixed Service systems operating in the bands 92-94 GHz, 94.1-100 GHz, 102-109.5 GHz and 111.8-114.25 GHz”, approved September 2018

[23] Recommendation ITU-R F.699-8: “Reference radiation patterns for fixed wireless system antennas for use in coordination studies and interference assessment in the frequency range from 100 MHz to 86 GHz”

[24] Recommendation ITU-R F.1245-3: “Mathematical model of average and related radiation patterns for point-to-point fixed wireless system antennas for use in interference assessment in the frequency range from 1 GHz to 86 GHz”

[25] ERC Report 025 : "The European table of frequency allocations and applications in the frequency range 8.3 kHz to 3000 GHz", approved June 1994, latest amended July 2022

[26] ITU Radio Regulations Edition 2020

[27] ETSI EN 302 217-4 " Fixed Radio Systems; Characteristics and requirements for point-to-point equipment and antennas; Part 4: Antennas"

[28] ECC Report 190: " Compatibility between Short-Range Devices (SRD) and EESS (passive) in the 122 to 122.25 GHz band", approved May 2013

[29] Recommendation ITU-R M.1732-1: "Characteristics of systems operating in the amateur and amateur-satellite services for use in sharing studies"

[30] M. -D. Kim, K. -W. Kim, H. K. Kwon, J. Lee and J. Park: "Experimental Reflection Characteristics of 253 GHz in a Small Closed-room," 2020 International Symposium on Antennas and Propagation (ISAP), 2021, pp. 689-690, doi: 10.23919/ISAP47053.2021.9391212

[31] https://fr.wikipedia.org/wiki/Liste_des_aires_urbaines_de_France

[32] https://en.wikipedia.org/wiki/List_of_metropolitan_areas_in_Spain

[33] ETSI EN 303 883-1: “Short Range Devices (SRD) and Ultra Wide Band (UWB); Part 1: Measurement techniques for transmitter requirements”

[34] Report ITU-R M.2322.0: "Systems characteristics and compatibility of automotive radars operating in the frequency band 77.5-78 GHz for sharing studies"