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# ANALYSIS OF POTENTIAL IMPACT OF MOBILE VEHICLE RADARS (VR) ON RADAR SPEED METERS (RSM) OPERATING AT 24 GHz

**Bordeaux, September 2009**

# 0 EXECUTIVE SUMMARY

This study considers the analysis of the potential impact of Vehicle Radars (VR) on radar speed meter (RSM) operating at 24 GHz, and derives technology neutral conditions for the protection of RSM.

The VR has a maximum transmit power of 100mW e.i.r.p (20 dBm) and occupies a bandwidth ≤ 200 MHz in the range from 24.05 GHz to 24.25 GHz.
The RSM has a transmit power of 20 dBm and a typical receiver bandwidth of 40 kHz.

The compatibility issue between both systems aforementioned only concerns the frequency band 24.075-24.150 GHz where the RSM is likely to operate. There is no compatibility issue between VR and RSM in the bands 24.05-24.075 GHz and 24.15-24.25 GHz.

The theoretical interference study (sections 3 and 4) shows that a VR interference power of 20 dBm without further mitigation techniques results in a harmful interference of the RSM and a reduction of the power to about -10 dBm would be needed for compatibility. The studies further considers mitigation techniques and comes to the result that the reduction of the VR time spent within the RSM bandwidth improves the situation and can ensure the compatibility, what can be seen as a kind of Duty cycle limitation.

From the measurements (see section 5), it can be concluded that for VR operating with a transmitting power below -10dBm no additional restriction is needed. For VR operating with a transmitting power below 20dBm an additional constraint should be considered in order to decrease:

- The number of RSM measurements samples possibly interfered
- The probability of having a VR transmitting at the time when the RSM is conducting measurements

Based on those results the following requirements are proposed for the band 24.075-24.150 GHz:

1. For VR operating with a transmitting power ($P_{VR}$) below about -10 dBm (e.i.r.p): no additional restrictions are required.
2. For VR operating with a transmitting power ($P_{VR}$) below 20 dBm (e.i.r.p) behind a bumper and a **fast** frequency modulation in comparison to a single RSM measurement. Therefore the time the VR emissions is dwelling in the RSM receiver bandwidth has to be limited to guarantee the VR doesn't cause interference. The investigation shows that this is achieved when the cumulated dwell time (DT – see section 4.1) of the VR in the RSM receiver bandwidth of 40 kHz is below 4 µs within any 3ms[1].
3. For VR operating with a transmitting power ($P_{VR}$) below 20 dBm (e.i.r.p) behind a bumper and a **slow** frequency modulation in comparison to a single RSM measurement. Such systems may remain for more than 4µs within the RSM receiver bandwidth and therefore, could interfere *individual* measurement samples. Such systems should not be allowed to interfere with more than one out of ten consecutive RSM measurements. This is ensured by limiting the dwell time (DT – see section 4.1) of the VR in the RSM receiver bandwidth of 40 kHz to 1ms within any 40ms.

The Report concludes the systems are compatible as long as the VR fulfils (1) or (2) or (3).

[1] If mounted without a bumper or in front of the bumper, the VR with 20 dBm e.i.r.p should respect a maximum DT of 3 µs within any 3 ms.

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## LIST OF ABBREVIATIONS

| **Abbreviation** | **Meaning** |
|---|---|
| Ae | Effective aperture |
| BL | Bumper loss |
| CEPT | European Conference of Postal and Telecommunications Administrations |
| DT | Dwell Time |
| e.i.r.p | Equivalent Isotropically Radiated Power |
| LNA | Low Noise Amplifier |
| MBR | Multi Beam Radar (same as VR) |
| Q | Quality factor |
| RCS | Radar Cross Section |
| RSM | Radar Speed Meter |
| TS | Target Strength |
| VR | Vehicle Radar (same as MBR) |

**Analysis of Potential Impact of Mobile Vehicle Radars (VR) on radar Speed Meters (RSM) operating at 24 GHz**

# 1 INTRODUCTION

Radar speed meters operated by police forces at 24 GHz play a major role within some administrations in national road safety policy. They are operated in some CEPT administrations by restricted categories of users under the **Radiolocation service**. Therefore these systems do not operate on a non-interference non-protected basis as SRDs do in the frequency band 24.05-24.25 GHz (f band for SRDs in Annex 6 of ERC/REC 70-03): they require an adequate protection from harmful interference, at least under national legislation in some CEPT administrations.
In such countries there were concerns that the legal basis for speed enforcement could be undermined if unlicensed emitters were allowed into the same environment. The concern is particularly acute in case of vehicular radar systems, which can be divided into 3 categories:

1. UWB SRR systems:
   Decision ECC/DEC/(04)10 on UWB SRR systems identifies frequency band 24.050-24.250 GHz for the narrow-band emission mode/component, which may only consist of an unmodulated carrier (e.g. residual carrier or optional Doppler radar signal). As explained in CEPT Report 003, tests showed low probability of narrow-band signals emitted by UWB-SRR sensors to fall within the RSM receiver bandwidth. This low probability of interference is however directly related to the type of narrow-band emission component of 24 GHz UWB-SRR sensors.

2. “Narrow-band” radar systems operating in the band 24.15-24.25 GHz
   100 MHz bandwidth and 100 mW e.i.r.p radar systems do not raise any compatibility problem with RSM since coexistence is simply achieved by frequency decoupling. However there is a high interest to use the entire 200 MHz ISM/SRD bandwidth and these radars are not allowed to do so because of the national restrictions in some CEPT administrations .

3. “Narrow-band” radar systems, operating within the band 24.050-24.250 GHz
   200 MHz bandwidth and 100 mW e.i.r.p radars without any restrictions may have the potential to interfere with RSM. However interferences may be limited thanks to some frequency modulation technique. It has to be noted that tests performed in 2004 with FMCW showed that setting a minimum frequency sweep speed avoids blocking of the police RSM. Power limits reduced to 20 mW (+13 dBm) mean e.i.r.p. and 50 mW (+17 dBm) peak e.i.r.p. were also found to address worst case interference scenarios. As a consequence the French regulation only authorizes FMCW signals with 20 mW mean e.i.r.p.

Some CEPT administrations proposed their national technical restrictions as a basis for a “class 1” under RTT&E description in the band 24.050-24.250 GHz. However it was argued that the FMCW modulation was not technologically neutral.

Therefore, this Report studied the potential interference situation between RSM and 100 mW e.i.r.p vehicle radars operating within this band in order to describe in a technology neutral manner the spectral characteristics of radar systems.

It was proposed to limit the studies to the worse case interference situation, corresponding to the vehicle radar radiating into the RSM mean beam.

This Report considers the compatibility between 100mW vehicle radars operating within the band 24.05-24.250 GHz and RSM, and derives technology neutral conditions for the protection of RSM in the band 24.075-24.15 GHz.

# 2 INPUT PARAMETERS AND SCENARIO DEFINITION

## 2.1 Victim (RSM) characteristics

The RSM has a transmit power of 20dBm e.i.r.p and a typical receiver bandwidth of 40 kHz. The carrier frequency of the RSM is typically not stabilized and may changes within the bandwidth of the RSM. Table 1 gives important analogue characteristics of the RSM which are considered in the study.

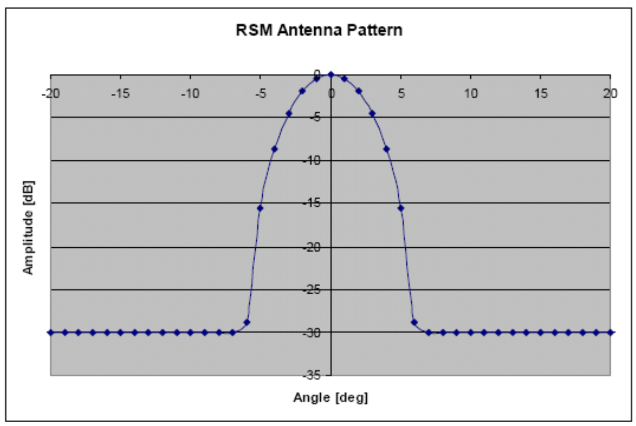
| | |
|---|---|
| Emission power | $P_{RSM}$ = -7 dBm |
| Receiver bandwidth | $B_{RSM}$ = 40 kHz |
| Noise floor | The receiver noise floor of a receiver is given by the thermal noise floor plus the noise added by the receiver. For a RSM with integrated LNA, we have :<br>-174 dBm/Hz+10*log(40 kHz)+3.3 dB = -124.7 dBm |
| Antenna | Gain : 27 dB, Sidelobe rejection: -30 dB<br>Pattern : The RSM has a horn antenna for the receive and transmit path In this Report, a one way half power beam width of **5°** is assumed. The shape is approximated by a $\cos^2$ function as shown below.<br><br>**Figure 1: RSM antenna pattern** |
| Signal processing | Digital, more details in the following |

**Table 1: Victim (RSM) input parameters**

A final vehicle speed measurement as well as a quality factor Q are derived from several individual RSM measurements, each lasting Tmeas (see Figure 2).

| M1 | M2 | M3 | M4 | M5 | M6 | M7 | M8 | M9 | M10 |
|---|---|---|---|---|---|---|---|---|---|
| $B_{RSM}$<br>Tmeas | $B_{RSM}$<br>Tmeas | $B_{RSM}$<br>Tmeas | $B_{RSM}$<br>Tmeas | $B_{RSM}$<br>Tmeas | $B_{RSM}$<br>Tmeas | $B_{RSM}$<br>Tmeas | $B_{RSM}$<br>Tmeas | $B_{RSM}$<br>Tmeas | $B_{RSM}$<br>Tmeas |
| ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ |
| Vehicle speed and quality factor Q | | | | | | | | | |

**Figure 2: Example of a RSM measurement process with 10 individual measurements**

During each individual measurement, the transmit frequency periodically alternates between two frequencies and a number of time samples is taken and then a FFT applied to obtain spectral information. Using the well known equation for the Doppler effect, the spectral information is related to a speed information:

f_signal (Hz) = 40.54 * v (km/h) or v (km/h) = 0.02467 * f_signal (Hz)

The quality factor approximately ranges from ca 3 to 6.8. The maximum value is reached when all individual speed measurements are validated and coherent. When the quality factor is lower than 3, the final vehicle speed is systematically rejected. For quality factor values in between, the acceptation of the vehicle speed is not certain.

## 2.2 Interferer (VR) characteristics

The VR has a maximum transmit power of 100 mW EIRP (20dBm) and occupy a bandwidth ≤ 200MHz in the range from 24.05 GHz to 24.25 GHz. This Report analyses the compatibility for two types of vehicular radars:

- VR with a max. e.i.r.p of 20 dBm and a **fast** frequency modulation in comparison to a single RSM measurement;
- VR with max. e.i.r.p of 20 dBm and a **slow** frequency modulation in comparison to a single RSM measurement;

To be technology neutral, for interferers only the data given in Table 2 are assumed while the modulation can be arbitrary.

| | |
|---|---|
| Transmitted Frequency | In the frequency range 24.05 GHz … 24.25 GHz |
| Transmitted Power | 100 mW (20 dBm) EIRP |

**Table 2: Interferer (VR) input parameters**

## 2.3 Interference scenario

Figure 3 describes the geometrical configuration of a <u>typical</u> interference scenario.

Offset RSM to road : 5m
Pointing direction RSM : 24°
Offset car to lane margin : 0.8m

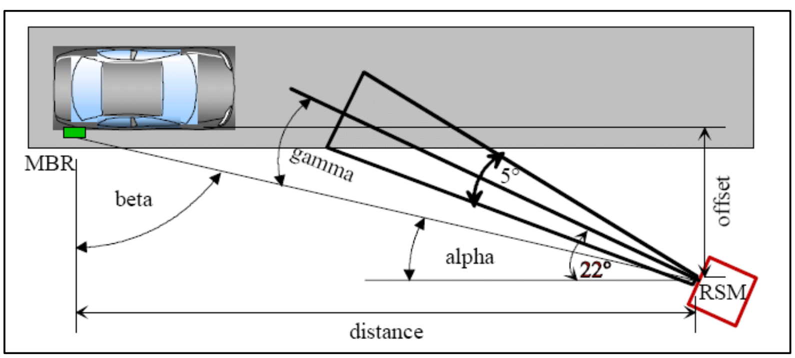



**Figure 3: Key scenario for interference assessment (MBR is the VR)**

The worse case (maximum antenna gain of the RSM) of this typical scenario occurs when beta is 66°, RSM and MBR at the same height. The typical distance between the RSM and the VR is then d=5/sin(24°)=12.3 m.

<u>Time spent by the vehicle radar in the RSM main beam:</u>

When the car approaches towards the RSM, it is located in the RSM main beam when alpha (see Figure 3) is within the range 24°± 2.5°. With a 5m offset, this corresponds to a longitudinal distance of 2.66 m=5 m*(1/tan(21.5)-1/tan(26.5)).

Let S be the vehicle speed:

If S=50 km/h, the VR remains 192 ms in the RSM main beam
If S=300 km/h, the VR remains 32 ms is in the RSM main beam.

**The time spent by the VR in the RSM main beam is much longer than the VR emission cycle (a few ms), thus a static calculation when alpha equals 24° is hereafter considered.**
During a part of this time, measurements are realized by the RSM to elaborate a speed value.

This also holds true for a worst-case distance of 35 m when the RSM is used for speed control of three lanes.

### 2.4 RSM protection criteria

According to the tests carried out in Rambouillet in June 2008 [1] (see also Annex 2), a protection criterion of C/I=20 dB and 6 dB preserve a quality factor of the MESTA 210C respectively above 6 and 3, with a 100% time interfering signal.

It is proposed to adopt a **protection criterion of C/I=8 dB**. This value seems adequate if one wants to be coherent with the CETECOM tests (see Annex 1) performed in 2004 (from which the current French regulation stems) where conclusions were based on a Q factor above or below 3, which corresponds to C/I=6 dB according to the Rambouillet tests (see Annex 2). A margin of 2 dB is proposed given the tests uncertainties, and given information from SAGEM which confirmed that the C/I protection criterion corresponding to a Q factor above 3 is between 6 dB and 10 dB.

## 3 INITIAL INTERFERENCE CALCULATION

### 3.1 RSM wanted received power

To calculate the RSM received power, one has to use the radar equation, which can be written for received power c in natural values as:

$$c = \frac{p_{RSM} \cdot g_{RSM}}{4\pi R^2} .\sigma. \frac{A_e}{4\pi R^2} \tag{1}$$

with $\sigma$ the radar cross section and Ae the effective aperture of the receiving antenna.
The following formula links Ae with the receiver antenna gain:

$$A_e = \frac{g_{RSM}\lambda^2}{4\pi} \tag{2}$$

When substituting (2) in (1), it comes:

$$c = \frac{p_{RSM} \cdot g_{RSM}}{\left(4\pi R^2\right)^2} .\sigma. \frac{g_{RSM}\lambda^2}{4\pi} = p_{RSM} .\left(g_{RSM}\right)^2 . \underbrace{\frac{4\pi\sigma}{\lambda^2}}_{ts} . \left(\underbrace{\left(\frac{\lambda}{4\pi R}\right)^2}_{PL}\right)^2 \tag{3}$$

Translated in dB, this leads to the following formula:

$$C = P_{RSM} + 2G_{RSM} + TS + 2PL \tag{4}$$

with:

TS : Vehicle Target Strength, defined as

$$TS = \text{RCS} + 10Log\left(\frac{4\pi}{\lambda^2}\right)$$

RCS : Radar cross section
$P_{RSM}$ : RSM power emission level (-7 dBm)
PL : Free space propagation loss (equal to $10*\log(\lambda^2/(4\pi d)^2)$)
$G_{RSM}$ : RSM antenna gain (~27 dBi)

The RCS value depends on the reflector shape and the direction of the measurement system. Annex 3 provides more information about RCS, and concludes that a mean RCS value of 5 dBm2 can be used for this compatibility study.

At 12.3 m and 35 m distances, given the RSM characteristics in Table 1, we get:

| | | |
|---|---|---|
| Lambda | m | 0,0125 |

| | | | |
|---|---|---|---|
| Distance | m | 12,3 | 35 |
| PL | dB | -81,8 | -90,9 |
| RCS | dB | 5 | 5 |
| TS | dB | 54,1 | 54,1 |
| $P_{RSM}$ | dBm | -7 | -7 |
| $G_{RSM}$ | dBi | 27 | 27 |
| **C** | **dBm** | **-62,6** | **-80,8** |
| N | dBm | -124,7 | -124,7 |
| **C/N** | **dB** | **62,1** | **43,9** |

**Table 3: wanted radar signal received by the RSM at 12.3m and 35m (maximum range)**

Therefore the wanted signal received by the RSM is C=-81 dBm and -63 dBm respectively at 35 m and 12.3 m, and thus C/N between 44 and 62 dB.

## 3.2 Basic interfering power

The interfering power I received by the RSM becomes:

$$I = P_{VR} + G_{VR} + PL + G_{RSM} - BL \quad (5)$$

where:

- I : Interference level received by the RSM
- $P_{VR}$ : VR power emission level (~20 dBm)
- $G_{VR}$ : VR antenna gain (0 dBi)
- PL : Free space propagation loss (equal to $10*\log(\lambda^2/(4\pi d)^2)$
- $G_{RSM}$ : RSM antenna gain (~27 dBi)
- BL : Bumper loss (1.5 dB)

| | | |
|---|---|---|
| Lambda | m | 0,0125 |

| | | | |
|---|---|---|---|
| Distance | m | 12,3 | 35 |
| PL | dB | -81,8 | -90,9 |
| $P_{VR}$ | dBm | 18,5 | 18,5 |
| $G_{VR}$ | dBi | 0 | 0 |
| $G_{RSM}$ | dBi | 27 | 27 |
| **I** | **dBm** | **-39,3** | **-48,4** |
| N | dBm | -124,7 | -124,7 |
| **I/N** | **dB** | **85,4** | **76,3** |
| C | dBm | -62,6 | -80,8 |
| **C/I** | **dB** | **-23,3** | **-32,4** |

**Table 4: Interference signal received by the RSM at 12.3m and 35m (maximum range)**

For d = 12.3m, I equals -39 dBm, thus I/N=85 dB and C/I equals -23 dB (approximately).
For d = 35m, I equals –48 dBm, thus I/N=76 dB, and C/I equals -32 dB.

The lower C/I and I/N values corresponds to the maximum distance of 35 m. Since the protection of RSM must be guaranteed in any configuration, compatibility conditions will be derived consequently considering the worse case scenario, which corresponds to the VR in the RSM main beam at a 35 m separation distance.

# 4 THEORETICAL INTERFERENCE STUDY

This section aims at deriving a compatibility condition between vehicle radars and RSM based on theoretical considerations where additional mitigation factors are taken into account.

## 4.1 Mitigation factors

In order to calculate the interference level falling into each RSM elementary measurement (see Figure 3), one must consider the following mitigation factors:

- probability for the interfering signal to fall into the RSM elementary measurement bandwidth, called PF (for probability factor)
- dwell time DT of the interfering signal into the RSM bandwidth during an individual RSM measurement, called DTF (dwell time factor).

**Probability factor (PF)**

When the VR emission frequency takes N different values distributed over a frequency modulation range Bvr much larger than the RSM reception bandwidth (Brsm), the probability factor accounts for the probability of the VR frequency to fall into the RSM reception bandwidth $B_{RSM}$. It can be expressed as:

$$PF = 10 \log (Nrsm / Nvr)$$

with:
- Nrsm the number of points falling into the frequency range Brsm
- Nvr the total number of points over the frequency range Bvr

For a discrete VR signal with N different values homogeneously distributed over Bvr, we have:
- Nrsm = Brsm* N/Bvr
- Nvr = N

Therefore

$$PF = 10 \log (Brsm / Bvr)$$

For a continuous VR signal such as FMCW with a frequency sweep speed S over Bvr during Ton, we have:
- Nrsm = Brsm* S
- Nvr = Bvr * S

Therefore

$$PF = 10 \log (Brsm / Bvr)$$

So for VR signals with a discrete (homogeneously distributed) or continuous sweeping frequency in Bvr, we have:

$$\mathbf{PF = 10 \log (Brsm / Bvr)} \qquad (6)$$

Nota : is has to be noted that pulsed signals with instantaneous bandwidth Bvr (but no modulation), the above mitigation still holds but does account for the power falling into the RSM elementary measurement bandwidth instead of the probability for the interfering signal to fall into the RSM bandwidth. Therefore Eq (6) above applies for both pulsed and frequency modulated signals, Bvr representing either the instantaneous frequency bandwidth or frequency modulation range.

**Dwell time mitigation factor DTF**

When the interfering signal hits the Brsm bandwidth, the interference level calculation must account for the dwell time DT of the interfering signal into the RSM bandwidth during an individual RSM measurement (lasting Tmeas). Indeed the perceived power by the RSM is not the VR peak power but only its part falling into the RSM bandwidth during the elementary measurement process (rectangle common to the pink and blue area in Figure 5, the part of the VR signal crossing it being tainted in red). Therefore a mitigation factor DTF due to the reduced time spent in the reception bandwidth during an elementary RSM measurement must be added into the calculation of I.

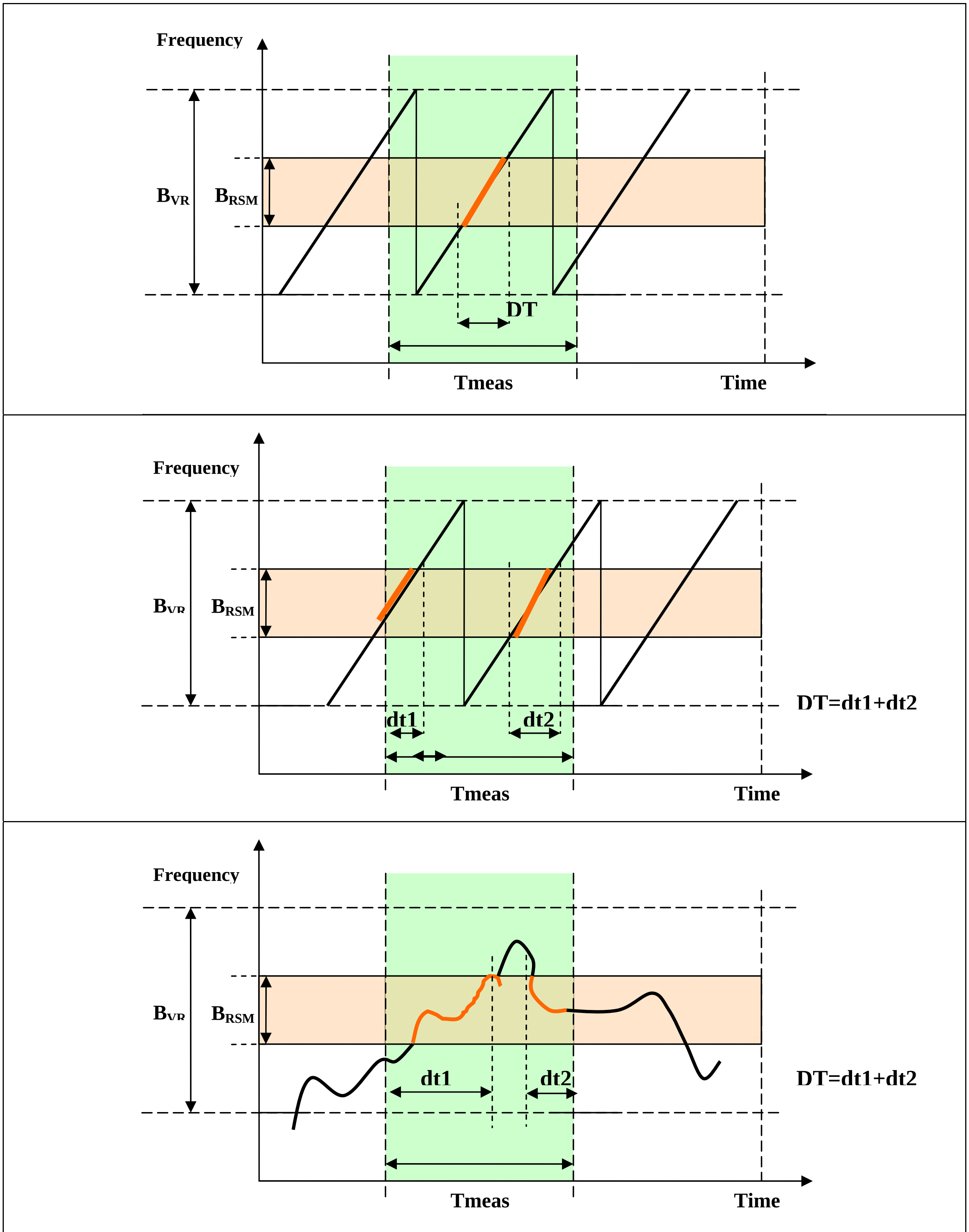



**Figure 5: Dwell time for various monofrequency VR signals**

$$\mathbf{P_{avg} = P_{peak} + 10 \log (dtf)} \tag{7}$$

where:

$P_{avg}$ : interference level received by the RSM during an elementary measurement (i.e inside a 40 kHz bandwidth during Tmeas)
$P_{VR}$ : average power received by the RSM from the VR (dBm)
$P_{peak}$ : VR peak power (Ppeak=$P_{VR}$)
dtf : "dwell time factor" equal to the ratio of VR dwelling time DT over the RSM time for one individual measurement Tmeas

dtf=DT / Tmeas if DT ≤ Tmeas, 1 otherwise

Therefore let us define DTF=10*log(dtf) as the averaging mitigation factor in dB.

*Note: DTF is similar to an apparent duty cycle since it accounts for the ratio of the time spent by the VR in the RSM over the RSM measurement time.*

**Other factors**

Duty cycle: if the VR signal has a duty cycle dc=Ton / (Ton + Toff), it must be added as a mitigation factor.

It must be noted that more than one VR could interfere with the RSM, in that case an accumulating factor can't be excluded. However to prevent interfering between themselves, collocated vehicle radars will be desynchronized. Therefore it is very unlikely that 2 radars (or more) simultaneously emit in the RSM reception bandwidth

Additional mitigation due to the signal processing may be considered. Indeed the RSM make several individual measurements to derive an estimation of the vehicle speed and a quality factor, but not each individual measurement is interfered. This may improve the C level.

### 4.2 Interference level calculation

Taking into account the various mitigation factors mentioned above, the interfering power I received by the RSM from the MBR is:

$$\mathbf{I = P_{VR}+DTF+G_{VR}+PL+G_{RSM}+PF-BL} \tag{8}$$

with:

I : interference level received by the RSM during an individual measurement
$P_{VR}$ : VR power emission level (~20 dBm)
$G_{VR}$ : VR antenna gain (0 dBi)
PL : free space propagation loss (equal to $10*\log(\lambda^2/(4\pi d)^2)$)
$G_{RSM}$ : RSM antenna gain (~27 dBi)
PF : probability factor equal to 10 log ($B_{RSM}$ / $B_{VR}$ ) if Bvr≥Brsm, 0 otherwise
DTF : dwell time factor equal to 10*log( DT/Tmeas) if DT ≤ Tmeas, 0 otherwise
BL : bumper loss (1.5 dB)

It must be noted that PF and DTF are either negative or nil.

### 4.3 Compatibility study

With a protection criterion of $C/I_{limit}$ =8 dB (see section 3.4), the required condition for compatibility is

$$C-I > 8 \text{ dB}$$

Expressing C from Equation (4) and I from equation (7) one gets:

$$C-I=Prsm+Grsm+TS+PL- P_{VR}-G_{VR}-PF-DTF+BL$$

and the interference level from VR is acceptable if:

$$Prsm+Grsm+TS+PL+BL- P_{VR}-G_{VR}-PF-DTF \geq C/I_{limit} \tag{9}$$

Introducing *A= Prsm+Grsm+TS+PL+BL-*$G_{VR,}$ we have

$$A\text{-}PF\text{-}DTF\text{-}P_{VR} \geq C/I_{limit} \qquad (10)$$

when considering the worse case interfering scenario at 35 m distance with RCS=5 $dBm^2$, Prsm=-7 dBm, Grsm=27 dB, BL=1.5 dB, Gvr=0 dB, A equals -14 dB ( A = -7 + 27 + 54 – 91 + 1.5 = -15.5) and (10) becomes:

$$PF+DTF+P_{VR} \leq -23.5 \text{ dBm} \qquad (11)$$

(let us recall that PF and DTF are negative terms).

**Discussion**

Eq (11) lead to much more stringent limitations than the current French regulation on VR signals in 24.05-24.25 GHz.
As a matter of fact, the French regulation allows FMCW signals with a sweep speed of 5 MHz/ms and 17 dBm emission power (e.i.r.p., no restriction on bumper loss): this lead to DTF = -25.7 and PF=0 (since there are no constrains on a minimum modulation frequency range), thus PF+DTF+Pvr = -8.7 and Eq (11) is not respected by about 14.5 dB.
The same for CW signals with Pvr = -10 dBm: they are allowed in one CEPT country without limitation on DT, which means that DTF = 0. Since here PF = 0 (CW signal, no modulation frequency range), PF+DTF+Pvr = -10 dB and Eq (11) is not respected by 13.5 dB.
Therefore it is proposed that the theoretical threshold on the right handside of Eq (11) be decreased by 10 dB, in order to derive compatibility conditions which would not be more stringent than the current French regulation (which is most stringent among the European countries). And thus VR signals should comply with the following revised condition:

$$PF+DTF+P_{VR} \leq -13.5 \text{ dBm} \qquad (11bis)$$

Application for VR signals with 20 dBm emission power

with Pvr=20 dBm (and a 1.5 dB bumper loss) VR signals must comply with:

$$PF+DTF \leq -33.5 \text{ dB} \qquad (12)$$

with

DTF : dwell time factor equal to 10*log( DT/Tmeas) if DT ≤ Tmeas, 0 otherwise
PF : probability factor equal to 10 log ($B_{RSM}$ / $B_{VR}$ ) if Bvr≥Brsm,, 0 otherwise

From 11bis it can be seen that a reduction of the power to about -12 dBm would be needed for compatibility without mitigation techniques (PF=DTF=0 dB). The mitigation factors PF and DTF are improving the situation as they are reducing the VR time spent within the RSM bandwidth, what can be seen as a kind of Duty cycle limitation.
These lead to define the following compatibility conditions based on (12):

| DT | Bvr | Compatibility condition | Remark |
|---|---|---|---|
| DT≥3 ms | | Bvr ≥89 MHz<br>since (12) implies PF≤-33.5 | DTF=0 |
| DT≤3 ms | Bvr ≤ 40 kHz | DT ≤ 1.3 µs in any 40 kHz bandwidth every 3ms | DTF<>0 and PF=0 |
| | Bvr ≥ 40 kHz | Bvr/DT ≥ 30 *(DT in ms and Bvr in MHz)* | DTF<>0 and PF<>0 |

**Table 5: Compatibility conditions stemming from the theoretical approach**

Table 5 shows that if the frequency modulation bandwidth Bvr is larger than 89 MHz, then no additional limitation on DT is needed. Conversely, if DT ≤ 1.3 µs in any 40 kHz bandwidth every 3ms, then no additional constrain on Bvr is needed.

## 5 PRACTICAL INTERFERENCE STUDY

Section 4 considered the protection of RSM through the protection of each of the measurement samples. However, it is recognised that not all the measurements samples must be free of interference in order to properly assess the speed of a car. This section aims at deriving a compatibility condition between vehicle radars and RSM based on a practical approach taking into account experiments carried out in 2004 and 2008 (see Annexes 1 and 2).

### 5.1 Mitigation factors

Considering Figure 2, less than 100% interference time means that

a) not all but only a number **NI** out of the 10 individual RSM measurements are interfered

and / or

b) the interference time (dwell time **DT**) to an individual RSM measurement is shorter than Tmeas (see examples in Figure 5).

The motivation for the differentiation between these two cases a) and b) is that they denote two fundamentally different effects:

Case a) denotes a digital situation, namely NI of the 10 individual results are interfered, the others are not interfered. The NI interfered results can be sorted out by the RSM using a suitable algorithm.

Case b) denotes a more analogue situation: if some of the time samples taken during Tmeas are interfered, this means a more or less wide peak (DT) in the time samples (see Figure 6, left), transforming to increased noise in the spectrum (see Figure 6, right), reducing the distance between a desired peak frequency and the noise or even covering the desired peak. Depending on DT, a median filter or some other sophisticated filter approach (for example [4]) can eliminate it.

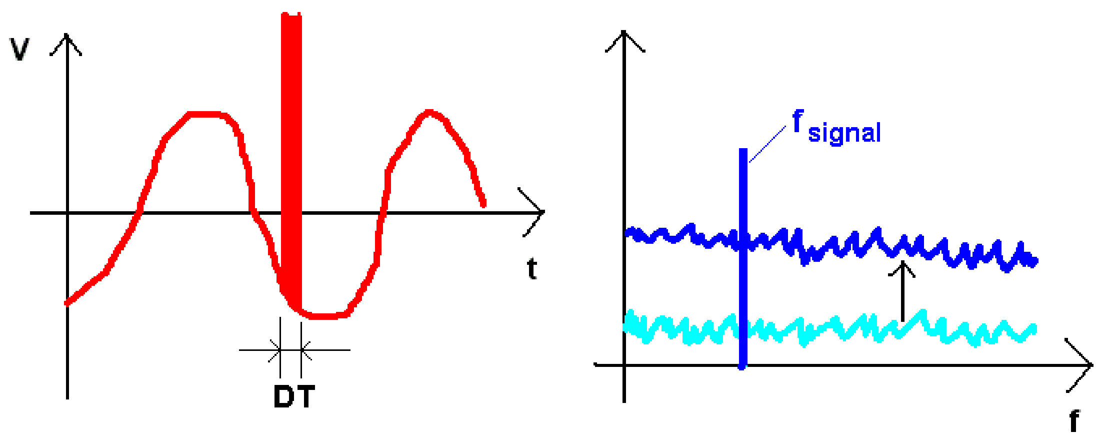



**Figure 6: Time limited interference to an individual RSM measurement (left) causing increased noise in the corresponding spectrum (right, moving noise from light blue to dark blue)**

Overall, the RSM with its digital signal processing is a nonlinear device, also its minimum required C/I depending on NI and / or DT is in general a nonlinear function. Furthermore, most RSM details like the number of used time samples per individual measurement are not published. Therefore it is difficult to derive a compatibility condition on a purely theoretical basis.

But in June 2008, some special combinations of NI and of DT were measured [1], see also annex 2. FMCW sweeps of 10ms duration and of different slope were used. With Tmeas = 3 ms, the 10ms FMCW duration means that 3 out of 10 individual RSM measurements are interfered, thus NI = 3. The different slopes mean different DT in the critical $B_{RSM}$.

In May 2004, also some special combinations of NI and of DT were measured [2], see also annex 1. For a FMCW sweep speed of 5 MHz / ms or more, a C / I of –49 dB was compatible. All considered sweeps had a duration of 10 ms. The sweep speed means DT/Tmeas = 0.27 % or less in the critical $B_{RSM}$ and NI=3.

The difficulty with measurement results are possible uncertainties caused by limited signal quality of the target reflector, antenna alignment, but these uncertainties should be covered by the available margin coming from the consideration of a worst case scenario.

Table 6 summarizes the available measured minimum required C/I results and other known values for the RSM quality factor Q ca. 3. It has to be noted that the structure of Table 6 does not cover more general situations where DT/Tmeas differs for interference with a first and a second individual RSM measurement.

| | **DT / Tmeas in %** | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **NI** | **0.0** | **0.1** | **0.27** | **0.4** | **1** | **4** | **10** | **50** | **100** |
| **0** | -∞ | -∞ | -∞ | -∞ | -∞ | -∞ | -∞ | -∞ | -∞ |
| **1** | -∞ | | | | | | | | |
| **2** | -∞ | | | | | | | | |
| **3** | -∞ | | -49[2] | -23.6[1] | -5.6[1] | 6.4[1] | 6.4[1] | (6.4) | (6.4) |
| **4** | -∞ | | | | | | | | |
| **5** | -∞ | | | | | | | | |
| **6** | -∞ | | | | | | | | |
| **7** | -∞ | | | | | | | | |
| **8** | -∞ | | | | | | | | |
| **9** | -∞ | | | | | | | | |
| **10** | -∞ | | | | | | | | 6.0[1] |

**Table 6: Measured or otherwise known minimum required C/I values in dB for RSM quality factor Q ca. 3.0, [1]=result from [1], [2]=result from [2], ( ) means interpolated or extrapolated result**

The results given in Table 6 show that for a given "NI", if the DT / Tmeas is decreased, a lower C/I may be accepted.

Now, applying the measured C/I values with equations (4) and (5), $P_{VR}$ can be derived as follow:

$$P_{VR} = Prsm + Grsm + RCS + 10\log(4\pi/\lambda^2) + PL - G_{VR} - C/I + BL \quad (13)$$

For the worst-case scenario with a distance of 35m and an RCS of 5dB, compatible $P_{VR}$ becomes:

$$P_{VR} = - C/I - 14$$

Table 7 shows the resulting $P_{VR}$ values for different values of NI and of DT for values of the RSM quality factor Q > 3.
Table 7 also includes results of tests performed in [3]. There, a single tone interferer of –10dBm was compatible (Q ca. 3.0). Since the RSM periodically alternates between two transmit frequencies, a single tone interferer gives a DT / Tmeas = 50%.

| NI | DT / Tmeas in % | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | **0.0** | **0.1** | **0.27** | **0.4** | **1** | **4** | **10** | **50** | **100** |
| **0** | +∞ | +∞ | +∞ | +∞ | +∞ | +∞ | +∞ | +∞ | +∞ |
| **1** | +∞ | | | | | | | | |
| **2** | +∞ | | | | | | | | |
| **3** | +∞ | | 35[2] | 9.6[1] | -9.6[1] | -20.4[1] | -20.4[1] | (-20.4) | (-20.4) |
| **4** | +∞ | | | | | | | | |
| **5** | +∞ | | | | | | | | |
| **6** | +∞ | | | | | | | | |
| **7** | +∞ | | | | | | | | |
| **8** | +∞ | | | | | | | | |
| **9** | +∞ | | | | | | | | |
| **10** | +∞ | | | | | | | -10.0[3] | -20[1] |

**Table 7: Max. compatible $P_{VR}$ in dBm for RSM quality factor Q ca. 3.0,**
**[1]=result from [1], [2]=result from [2], [3]=result from [3], ( ) means interpolated or extrapolated result**

As becomes obvious, the three different measurement results in Table 7 are not fully consistent. The inconsistencies may be due to measurement uncertainties (see discussion above) as well as uncertainties stemming from the RCS calculation.

With some extrapolation, a kind of hyperbolic contour seems to describe the regions for a constant compatible $P_{VR}$, as sketched in Figure 7.

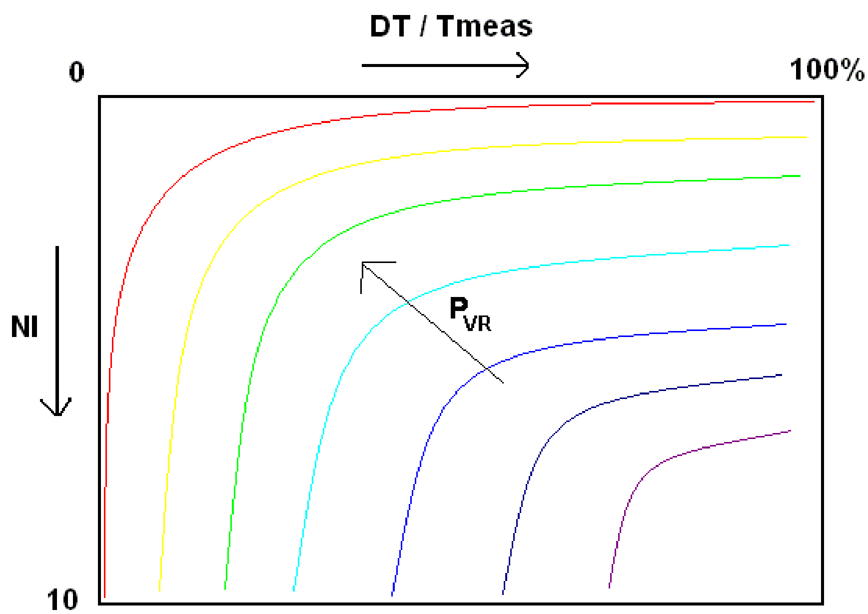



**Figure 7: Principle contours of constant compatible $P_{VR}$**

If more than one VR interferes with the RSM, an aggregating factor can't be excluded. However to prevent interfering between themselves, collocated VRs will be desynchronized. Therefore it is very unlikely that more than one radar simultaneously emit in the RSM reception bandwidth.

Recognizing the measurement uncertainties (see discussion above), additional material relating to the interpretation of the results of the measurements are provided in the next section for two cases of VR transmitted powers (-10 dBm and 20 dBm).

### 5.2 Conditions for compatibility

In this section, additional considerations are given to the results of measurement for VR transmitted powers of -10dBm and 20dBm are considered. It aims at identified condition / threshold under which an acceptable number of measurements samples is found depending of the VR transmitted power.

For $\mathbf{P_{VR}}$ **= +20 dBm**, in Table 8 now all situations are marked with a black square which are definitely compatible and with a grey square which are likely compatible.

| | DT / Tmeas in % | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **NI** | **0.0** | **0.1** | **0.27** | **0.4** | **1** | **4** | **10** | **50** | **100** |
| **0** | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ |
| **1** | ■ | ■ | ■ | ■ | ■ | ▓ | ▓ | ▓ | ▓ |
| **2** | ■ | ■ | ■ | ■ | | | | | |
| **3** | ■ | ■ | ■ | | | | | | |
| **4** | ■ | ▓ | ▓ | | | | | | |
| **5** | ■ | ▓ | ▓ | | | | | | |
| **6** | ■ | ▓ | ▓ | | | | | | |
| **7** | ■ | ▓ | ▓ | | | | | | |
| **8** | ■ | ▓ | ▓ | | | | | | |
| **9** | ■ | ▓ | | | | | | | |
| **10** | ■ | ▓ | | | | | | | |

**Table 8: Black = situations definitely compatible for $\mathbf{P_{VR}}$ = 20 dBm, grey = very likely compatible**

From Table 8, it can be concluded in the case of a 20 dBm VR, an additional condition on the DT / Tmeas is necessary to increase the number of measurement samples free of interference.

Now, either a nonlinear function of NI and of DT/Tmeas can be fitted to describe a compatibility condition for the black and grey squares, or the following verbal conditions for $P_{VR}$ = +20 dBm can be specified:

- if DT / Tmeas ≤ 0.2 % for an individual RSM measurement, then all individual measurements may be interfered
- if DT / Tmeas >0.2 % for an individual RSM measurement, then max. 1 out of 10 individual RSM measurements may be interfered

In the same way, compatible situations can be given for other power levels, for example for $\mathbf{P_{VR}}$ **= -10 dBm** in Table 9.

| | DT / Tmeas in % | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **NI** | **0.0** | **0.1** | **0.27** | **0.4** | **1** | **4** | **10** | **50** | **100** |
| **0** | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ |
| **1** | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ▓ |
| **2** | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ▓ |
| **3** | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | |
| **4** | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | |
| **5** | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | |
| **6** | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | |
| **7** | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | |
| **8** | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | |
| **9** | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | |
| **10** | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | |

**Table 9: Black = situations definitely compatible for $\mathbf{P_{VR}}$ = -10 dBm, grey = very likely compatible**

From that, taking into account that 100% interference is unrealistic because it would require an interferer that hits exactly both RSM frequencies, no condition for compatibility with Pvr = -10 dBm is proposed.

### 5.3 Proposal for abstract compatibility conditions

From the measurements, it can be concluded that for VR operating with a transmitting power below -10dBm no additional restriction is needed. For VR operating with a transmitting power below 20dBm an additional constraint should be considered in order to decrease:

- The number of measurements samples possibly interfered
- The probability of having a VR transmitting at the time when the RSM is conducting measurements

The obtained results can be formulated in the following, more abstract way:

| | |
|---|---|
| Pvr ≤ -10 dBm | No limitation for interference duration required |
| Pvr≤ +20 dBm (Pvr≤ +18.5 dBm in front of bumper) | Max. 6 µs interference in any 40kHz every (3+) ms, OR<br>Max. 1 ms interference in any 40kHz every (30+) ms |

**Table 10: Compatibility condition stemming from the practical approach**

## 6 CONCLUSIONS

The theoretical interference study (sections 3 and 4) shows that an VR interference power of 20 dBm without further mitigation techniques results in a harmful interference of the RSM and a reduction of the power to about -10 dBm would be needed for compatibility. The studies further considers mitigation techniques and comes to the result that the reduction of the VR time spent within the RSM bandwidth improves the situation and can ensure the compatibility, what can be seen as a kind of Duty cycle limitation.

From the measurements (see Table 10), it can be concluded that for VR operating with a transmitting power below -10dBm no additional restriction is needed. For VR operating with a transmitting power below 20dBm an additional constraint should be considered in order to decrease:

- The number of measurements samples possibly interfered
- The probability of having a VR transmitting at the time when the RSM is conducting measurements

Based on the results obtained in sections 4 and 5, results the following requirements are proposed for the band 24.075-24.150 GHz:

1. For VR operating with a transmitting power below about -10 dBm (e.i.r.p): no additional restrictions are required.
2. For VR operating with a transmitting power below 20 dBm (e.i.r.p) behind a bumper and a **fast** frequency modulation in comparison to a single RSM measurement. Therefore the time the VR emissions is dwelling in the RSM receiver bandwidth has to be limited to guarantee the VR doesn't cause interference. The investigation shows that this is achieved when the cumulated dwell time of the VR in the RSM receiver bandwidth is below 4 µs within any 3 ms[2].
3. For VR operating with a transmitting power below 20 dBm (e.i.r.p) behind a bumper and a **slow** frequency modulation in comparison to a single RSM measurement. Such systems may remain for more than 4 µs within the RSM receiver bandwidth and therefore could interfere several *individual* measurement samples. Therefore such systems are not allowed to interfere with more than one out of ten consecutive RSM measurements. This is ensured by limiting the dwell time to 1ms within any 40 ms.

The Report concludes the systems are compatible as long as the VR fulfils (1) or (2) or (3).

[2] If mounted without a bumper or in front of the bumper , the VR should respect a maximum DT of 3 µs within any 3 ms.

## ANNEX 1: SUMMARY OF MAY 2004 CETECOM TESTS

Tests were carried on at CETECOM in April 2004 between MESTA 208/210 and MBR operating at 24 GHz, involving VALEO, SAGEM, CELAR (French MoD) and CETECOM (German laboratory).
The purpose was mainly to demonstrate the interference risk between a RSM (MESTA 208 or 210) and a typical MBR.

*Two kinds of interferers were simulated:

- FMCW signals sweeping 1500 MHz in 10 ms with and EIRP between-5 dBm to 20 dBm
- FMCW signals sweeping 50 MHz/ms to1 MHz/ms with and EIRP of 20 dBm
- CW signals transmitting on the low, mid and high end of ISM band

**During these tests the interference source was kept at a distance of 2 m.**

* The measurements were conducted using a worse case scenario, where the RSM was pointing directly at the point of maximum emissions of the SRR, and a target simulator set just 6 dB above the sensitivity level of the RSM. More details are given below (the setup is shown in Figure A1.1).

Results are summarized below (only for MESTA 210):

**FMCW**
As soon as the MBR is active, and located in a position d<6.0 m to the MESTA, the quality level of the measurement is reduced. When the interferer is positioned in a distance <3.0 m, the measurement quality drop below 2.66. This is the threshold for a validated measurement. But despite of the poor quality for measurements where the interferer distance is 2m, the displayed speed is indicated correctly.
The accuracy of the speed measurement was not affected at any distance.

- for sweeps faster than 50 MHz/10 ms no influence could be observed. The quality level stayed at a constant level
- - for sweeps between 50 MHz/10 ms and 1500 MHz/10 ms
- for very slow sweeps of 50 MHz/10 ms the quality level was reduced. At a sweep of 10 MHz/10 ms the quality level was reduced from 3 to 2.7.

**These measurements show that there is no interference as long as the chirp of the frequency modulation is above 50MHz/10ms.**

**CW**
For the measurement a power level of +20 dBm was used. The interferer was placed at 2 meter distance to the RSM.
No interference or reduction of the quality level could be observed as long as the emitted CW tone was separated by 2.5 MHz or more from the RSM carrier. However such interference never resulted in wrong speed readout but rather in a display suppression.

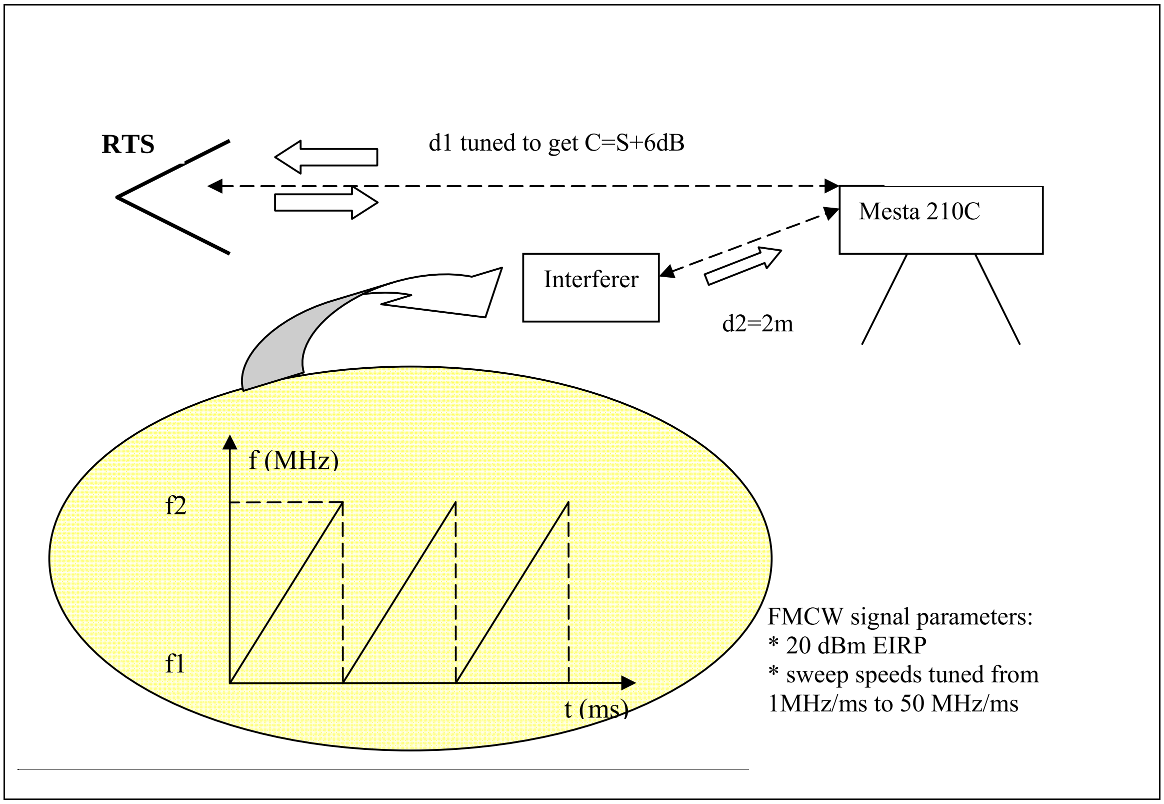



**Figure A1.1: May 2004 test setup**

The RSM sensitivity threshold was experimentally reached (meaning Q ca. 3.0) when the Radar target simulator (RTS) was located 4.95 meters from the RSM (in the line of sight in the main beam of the RSM and about 10 cm below the optical axis RSM-RTS). Then the RTS gain was tuned so that the C signal received by the RSM was set at the sensitivity threshold plus 6 dB (i.e. the RSM S/N ratio of 6 dB was meet). According to [2] the RTS then had an insertion gain of 34 dB. With a 4.95 m path loss of 74,5 dB and an RSM RX-antenna gain of 27 dBi that gives a value for C according to equation (4) of:

$$C = -7\text{ dBm} + 2 * 27\text{ dBi} + 34\text{ dB} – 2 * 74{,}5\text{ dB} = -68\text{ dBm}$$

For the interferer, equation (5) gives:

$$I = P_{VR} + G_{VR} + PL + G_{RSM}$$

with PL= -66 dB at 2 m

then gives $I = 20\text{ dBm} + 0 – 66\text{ dB} + 27\text{ dB} = -19\text{ dBm}$

and $C/I = -49$ dB for Q ca. 3.0.

## ANNEX 2: SUMMARY OF 2008 RAMBOUILLET TESTS

Figure A2.1 shows the minimum C/I levels needed according to the time ratio between the interfering signal in the RSM reception bandwidth and the RSM measuring time (for a single complete full measurement of a vehicle's speed):

- in blue the C/I level corresponding to the beginning of the degradation of RSM quality factor Q (6≤Q≤6.8)
- in pink the C/I level corresponding to the lower acceptable RSM quality factor Q values (2.8<Q≤5)

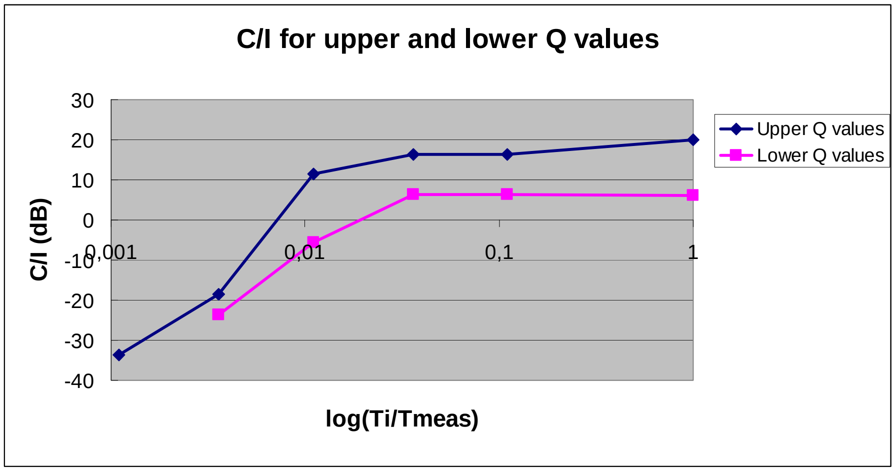



**Figure A2.1: Summarized minimum required C/I vs. Ti / Tmeas = DT / Tmeas**

## ANNEX 3: INVESTIGATION ON VEHICLES' RCS VALUES

The RCS value depends on the reflector shape, and the parameters of measurement antenna (beamwidth, direction…). Figure A3.1 below gives theoretical and simplified formula in the specular directions.

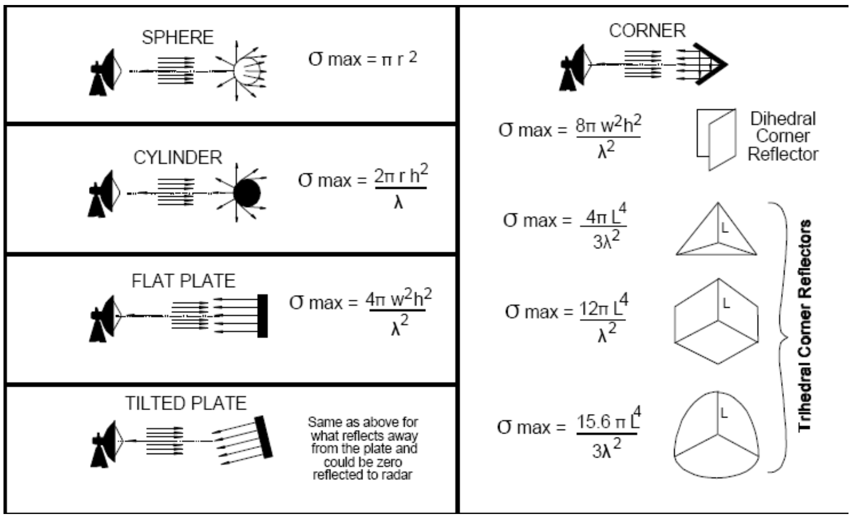



**Figure A3.1: Simplified RCS values for various reflector shapes in specular directions**

| | Vertical dimension | Horizontal dimension | **RCS (dBm²)** |
|---|---|---|---|
| Radius sphere | r =1 (d=2) | - - - | 5 dBm² |
| | r =0.75 (d=1.5) | - - - | 2.5 dBm² |
| | r =0.5 (d=1) | - - - | -1 dBm² |
| Flat conductive plate area | w =1 | h =1 | 49 dBm² |
| | w =1 | h =0.4 | 41 dBm² |
| Cylinder 1 | r =0.5 (d=1) | h =2 | 30 dBm² |
| | r =0.5 (d=1) | h =0.8 | 22 dBm² |
| | r =0.25 (d=0.5) | h =0.8 | 19 dBm² |
| Trihedral corner reflector | L =0.6 | - - - | 35 dBm² |

**Table A3.1 Theoretical RCS values in specular direction at 24GHz**

If the car is assimilated as a cylinder of 2 m long and 0.5 m radius, then its RCS is equal to 22 dBm² in the specular dimension.
This theoretical approach is simplified and gives RCS values in the specular direction, and can't take into account the 24° tilt of the system of measurement.

Results given above must be completed and clarified either with shape modelling (CAD), or with real measurements. Measurements realized within the French Defence on various vehicles in the X and Ka band showed that:

- RCS values are very dependant of the direction in which the measure is realised,
- RCS values in the 24° tilt are much lower than those mentioned above, as Figure A3.2 exemplifies.

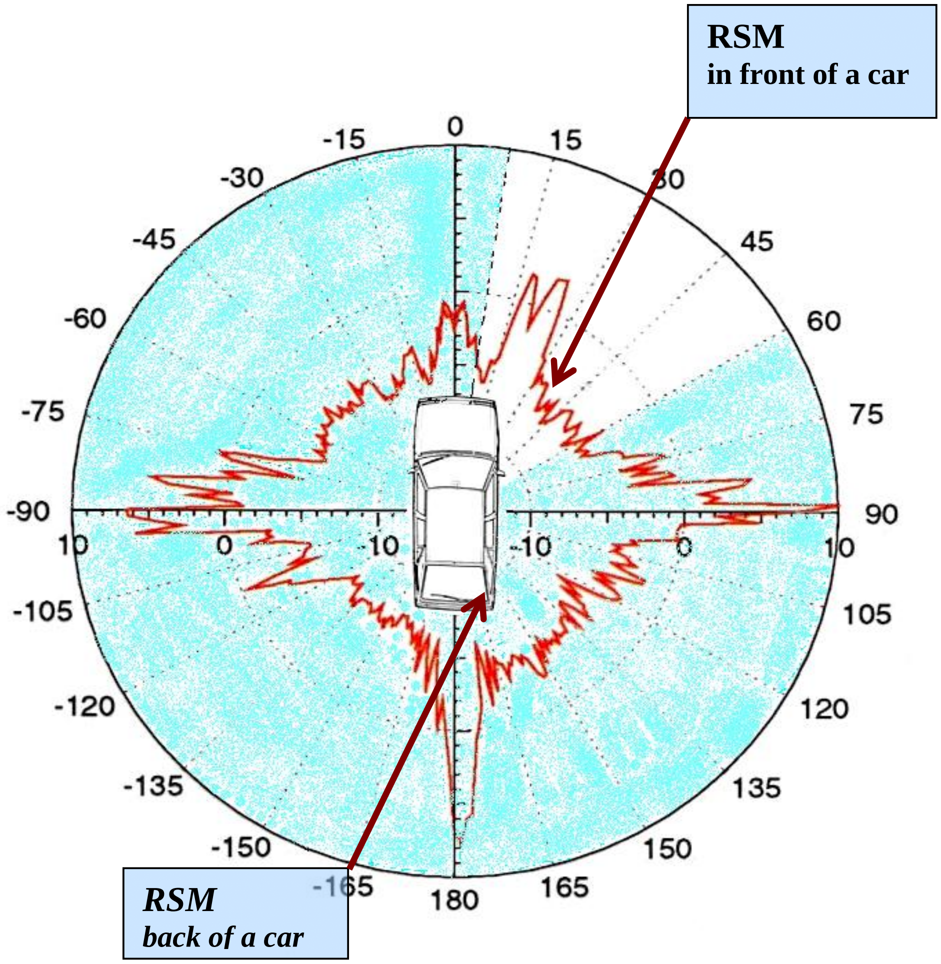



**Figure A3.2: RCS polar diagram of a *Citroen* BX vehicle. The possible RSM measurement directions are indicated**

In the angle of the RSM measurement (front and back of vehicles, see Figure A3.2), RCS values measured for various vehicles range from -3dBm$^2$ to 7dBm$^2$ as Table below exemplifies:

| RCS in the 25° | BX car | | 307 car | | Partner (van) | |
|---|---|---|---|---|---|---|
| | Front | Back | Front | Back | Front | Back |
| X Band (8,5-10,5 GHz) | 0dBm² | -3dBm² | 4dBm² | 3dBm² | | |
| 24 GHz band (24,1-24,4 GHz) | -1dBm² | | 3dBm² | | 9dBm² | |
| Ka Band (33/35 GHz) | | | | | 7dBm² | 7dBm² |

**Table A3.2: RCS - 25° values**

Therefore it is considered that a mean RCS value of 5 dBm$^2$ is representative as a mean value for the compatibility study between Radar Speed Meter and Vehicle Radars.

## ANNEX 4: LIST OF REFERENCES

[1] ANFR, 24GHz RSM Test Draft Report (Rambouillet measurements, June 2008), 2nd September 2008

[2] CETECOM, Test Report No. 2-3557-01-01 / 04, Interference Investigation VALEO MBR / MESTA 210, MESTA 208, May 2004

[3] CETECOM, Test Report No. 2-3500-01-01 / 04, Interference Investigation UWB-SRR / SAGEM MESTA 208, March 2004

[4] Valeo Raytheon Systems, System and Method for Reducing the Effect of a Radar Interference Signal, Patent WO 2008 / 082973 A1.