Evolution of marine radar: practical effects on vessel traffic safety

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Abstract—Sea shipping is characterized by a good delivery rate and affordable operating costs in comparison with other transport means, i.e. by road, rail or air. Hence, the continuous increase of vessel traffic, also related to the increasing environmental consciousness and the better attention paid to the primary resources (especially oil and raw materials), requires a high degree of control and an adequate assistance to the navigation, in order to ensure safety, reduction of risks for the environment, as well as an efficient navigation. The paper describes the evolution of the marine radar systems pointing out some potential drawbacks due to the implementation of solid state technology in next generation marine radars, with related interference problems.

Keywords—Vessel traffic; marine radar; radar interference.

I. INTRODUCTION

The widespread use of radar-based marine surveillance systems and the pertaining regulations goes back to the 1970’s when the International Maritime Organization (IMO) issued the “International Convention for the Safety Of Life At Sea” (SOLAS) which is recognized as the most important international treaty concerning the safety of ships [1], where the autonomous decision of maneuvering is delegated to the captain in compliance with the navigation rules. However, if the area is covered by the Vessel Traffic System (VTS), the ship may receive directly from the control authorities the directions on the route to follow. Moreover, thanks to the non-cooperative surveillance and navigation system, i.e. the radar system, and to the cooperative one installed on board, i.e. the Automatic Identification System (AIS) based on GPS data, it is possible to get an overall picture of the nearby maritime traffic.

Even in the Global Navigation Satellite System (GNSS) era, the on-board radar sensor remains of fundamental importance to avoid collisions with non-cooperating (e.g. small) vessels and obstacles of various kinds, and to visually acquire the coastline and the islands. Based on the IMO regulations [2]-[3], the main characteristics of marine radars are: frequency band from 9300 to 9500 MHz in the X-band and 2900-3100 MHz in the S-band, and for the acceptable values (worst case): range accuracy 30 m; angular accuracy 1°; range resolution 40 m; azimuthal resolution 2.5°; distance of detection from 5 nm for small ships to 20 nm for high coast (60 m); probability of detection 0.8; probability of false alarm 10⁻³.

The traditional marine radar systems are based on a low-cost commercial magnetron technology with relatively high peak power levels up to 12.5-50 kW [4] and small duty cycle, of the order of 2·10⁻⁴ ÷ 7·10⁻⁴. The simplicity and low-cost of these magnetron radars is, unfortunately, associated with the short life of the magnetrons themselves, of the order of one (or a few) thousand hours, therefore calling for a frequent and expensive maintenance.

In the recent years a new generation of marine radar is being developed using the solid-state transmitter technology. These radar systems have a lower cost of maintenance with MTBF (Mean Time Between Failures) of the order of 50000 hours and no high voltage circuitry. These systems work with low peak power (ten or hundred W) using pulse compression (coded pulse in transmission and matched filter in reception) with a variable duty cycle up to 10 %. A basic drawback of the use of “long pulse”, i.e. high duty cycle, has been known for many years, but not yet seriously considered till now, excluding a single paper, [5] (Section VII p. 163), where it is clearly stated: “the interference effects that such a radar might cause on existing marine radars may be catastrophic”. These effects become critical when the traffic density (number of ships per nm²) increases. Although today the solid-state marine radars still have minimal diffusion for the main suppliers, they are expected to represent the future for the marine systems and several companies are introducing them on the market. For this reason, it is very interesting to study the damaging effects of the mutual interferences among different marine radars, a topic which in our opinion has received too little attention till today.

The aim of this paper is to evaluate the reduction of detection capability when more radars (including solid-state ones) operate in mutual visibility conditions. This study starts from the definition of a statistical model for the mutual distance between pairs of radars, derived using real data.

II. HORIZON RADAR FOR DIFFERENT SHIPS

The visibility between a pair of ships (k, i) occurs when the distance \( R_{ki} \) of their radar antennas is less than (or equal to) the radar horizon \( R_h \). The visibility distance \( R_{ki} \), depending on the antenna heights \( h_k \) and \( h_i \), in standard atmosphere and using the equivalent earth radius \( r_e \equiv 8500 \text{ km} \), can be evaluated as [6]:

\[
\text{visibility distance } R_{ki} = \min\left( \frac{r_e}{\sin^{-1}\left(\frac{R_h}{r_e} - \frac{R_h}{R_h} \right)}, \frac{R_h}{\sin^{-1}\left(\frac{R_h}{r_e} - \frac{R_h}{R_h} \right)} \right).
\]
The radar antenna height above sea level is not a part of the vessel-derived AIS information. Therefore, in this study it had to be empirically estimated for each class of ship (passenger, cargo, fishing, …) by relating it to the ship length (available by the AIS message) using specialized websites [7]–[9].

Considering 13 classes for the ships (see Table I) and 10 samples for each class, 130 samples have been used to derive a non-linear regression equation (see Fig. 1) to evaluate $h$ (m) versus the ship length $x$ (m):

$$h = 0.7825 \cdot x^{0.728}$$

Fig. 1. Antenna height (m) vs ship length (m).

TABLE I. TYPES OF SHIPS

<table>
<thead>
<tr>
<th>No</th>
<th>IMO N°</th>
<th>Ship Type</th>
<th>Length Mean [m]</th>
<th>Length Mean [m]</th>
<th>Antenna Height Mean [m]</th>
<th>Antenna Height Mean [m]</th>
<th>Radar Horizon Mean [nm]</th>
<th>Radar Horizon Mean [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>50</td>
<td>Pilot</td>
<td>14</td>
<td>2</td>
<td>5</td>
<td>1.2</td>
<td>5</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>30</td>
<td>Fishing</td>
<td>26</td>
<td>4</td>
<td>7</td>
<td>1.0</td>
<td>5.9</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>37</td>
<td>Yacht (≤30m)</td>
<td>27</td>
<td>3</td>
<td>8</td>
<td>1.6</td>
<td>6.3</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>31/32/51</td>
<td>Towboat</td>
<td>25</td>
<td>5</td>
<td>10</td>
<td>1.9</td>
<td>7.0</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>40–49</td>
<td>High Speed Craft</td>
<td>82</td>
<td>15</td>
<td>16</td>
<td>2.0</td>
<td>8.9</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>37</td>
<td>Yacht (&gt;30m)</td>
<td>81</td>
<td>20</td>
<td>20</td>
<td>5.4</td>
<td>10.0</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>60–69</td>
<td>Passengers (&gt;150m)</td>
<td>96</td>
<td>32</td>
<td>22</td>
<td>5.0</td>
<td>10.4</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>55</td>
<td>Military</td>
<td>100</td>
<td>39</td>
<td>23</td>
<td>7.7</td>
<td>10.7</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>70–79</td>
<td>Cargo</td>
<td>112</td>
<td>29</td>
<td>24</td>
<td>4.8</td>
<td>10.9</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>60–69</td>
<td>Passengers (&gt;150m)</td>
<td>177</td>
<td>25</td>
<td>36</td>
<td>4.0</td>
<td>13.3</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>80–89</td>
<td>Tanker (&gt;250m)</td>
<td>206</td>
<td>40</td>
<td>40</td>
<td>6.0</td>
<td>14.1</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>80–89</td>
<td>Tanker (&gt;250m)</td>
<td>291</td>
<td>34</td>
<td>45</td>
<td>5.0</td>
<td>15.0</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>70–79</td>
<td>Container</td>
<td>337</td>
<td>68</td>
<td>56</td>
<td>6.4</td>
<td>16.6</td>
<td></td>
</tr>
</tbody>
</table>

III. STATISTICAL MODEL FOR THE DISTANCE BETWEEN SHIPS

In collaboration with the General Command of the Italian Coast Guard, using the AIS information a statistical model for

the mutual distance between a pair of ships has been estimated. Generally it depends on the observed marine area, but a Gamma model: $f_R(r) = \frac{\lambda^b}{\Gamma(b)} e^{-\lambda r} r^{b-1}$, is well suited to most data sets. The parameters $(\lambda, b)$ have been estimated by the Maximum Likelihood method. Considering the Central Tyrrhenian (near Naples) as shown in Fig. 2, it results: $\lambda = 2.047$, $b = 0.0624$. In another area, the central Adriatic, the values are different, i.e.: $\lambda = 2.15$, $b = 0.0387$.

Fig. 2. Dashed lines indicate all ships in radar visibility (45 total ships excluding those in harbour). Sea area near Naples, (Friday, 27/02/2015, h: 08:00 a.m.).

IV. PROBABILITY OF VISIBILITY AMONG SHIPS AND COMPARISON WITH REAL DATA

In the previous sections we have shown that the mutual distance $R_{ki}$ between the ships $(k,i)$ can be modelled by a random variable with a Gamma density function. A type $k$ ship sees the ship of type $i$ if and only if $R_{ki} \leq R_k + R_i$, i.e. indicating with $P_i$ the probability that the ship be of type $i = 1, 2, ..., N_{type}$, the probability of visibility can be written as:

$$P(\text{vis})_{ki} = \text{Prob}(R_{ki} < R_k + R_i) \cdot P_i$$

Generalizing, the probability that the ship $k$ sees any type of ship becomes:

$$P(\text{vis})_k = \sum_{i=1}^{N_{type}} P(\text{vis})_{ki} = \sum_{i=1}^{N_{type}} \gamma(b, \lambda, x) \cdot P_i$$

with $x = \lambda(R_k + R_i)$ and $\gamma(b, \lambda, x) = \frac{1}{\Gamma(b)} \int_0^x e^{-t} t^{b-1} dt$ the Incomplete Gamma Function. Varying $k$, the probability that any pair of ship be in visibility is given by:

$$P(\text{vis}) = \sum_{k=1}^{N_{type}} P(\text{vis})_k \cdot P_k$$
Considering the sea near Naples (see Fig. 2), the probability of visibility results equal to 27.7%. The Naples area shows a moderate traffic (45 ships with density of $6.72 \cdot 10^{-3}$ ships/mm²), with 44% of the fishing type, i.e. small ships with a limited antenna height, while 47% being large vessels (cargo, container, passengers and tankers) with high antenna height. It results that the maximum ship number that one ship sees, is 24 with an empirical mean of 10.71. Using the probability of visibility, $P(\text{vis}) = 0.277$, multiplying for the number of ships enroute (45), the mean value results equal to 12.46 i.e. a bit higher than the empirical one. Table II summarizes the results for the number of ships in visibility. In the last two columns the $50^\text{th}$ and the $20^\text{th}$ percentile are shown. Fig. 2 shows the peak vessel traffic, excluding those in a port. The dashed lines connect all ships in radar visibility.

<table>
<thead>
<tr>
<th>Max</th>
<th>Min</th>
<th>Ave (Data)</th>
<th>Ave (Model)</th>
<th>Dev. Std.</th>
<th>$50^\text{th}$ Percentile</th>
<th>$20^\text{th}$ Percentile</th>
</tr>
</thead>
<tbody>
<tr>
<td>24</td>
<td>1</td>
<td>10.71</td>
<td>12.46</td>
<td>6.65</td>
<td>12.5</td>
<td>2.5</td>
</tr>
</tbody>
</table>

Table II: Number of ships in visibility in sea near Naples.

After the analysis on both the maritime traffic and the visibility among ships, we will use the obtained results to evaluate the effects of radar interferences on the probability of detection.

V. MAIN CHARACTERISTICS OF MARINE RADARS

Table III reports the main parameters of marine radars with magnetron (MG) and solid-state (SS) technologies that will be used in the evaluation of the probability of detection.

<table>
<thead>
<tr>
<th></th>
<th>Magnetron (MG)</th>
<th>Solid-State (SS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>9410 MHz ± 30 MHz</td>
<td>9300-9500 MHz</td>
</tr>
<tr>
<td>Power</td>
<td>25 kW</td>
<td>50/100/200/400 W</td>
</tr>
<tr>
<td>$\tau$ [μs]/PRF [Hz]</td>
<td>0.08/3000</td>
<td>0.05 - 100 μs</td>
</tr>
<tr>
<td></td>
<td>0.15/3000</td>
<td>PRF = 350 - 2500 Hz</td>
</tr>
<tr>
<td></td>
<td>0.3/1500</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.5/1000</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.7/600</td>
<td></td>
</tr>
<tr>
<td>Typical duty cycle</td>
<td>2.4 \cdot 10^{-4}</td>
<td>0.05 – 0.2</td>
</tr>
</tbody>
</table>

Table III: Main parameters of typical marine radar

VI. PROBABILITY OF DETECTION

To evaluate the effects of the interferences on the probability of detection, we define the time of overlap $T_{\text{over}} = \tau_i + \tau_k$ as the interval with no interfering pulses, where $\tau_k$ and $\tau_i$ are the pulse-width of the ship $k$ (victim) and the ship $i$ (interfering) radar (independent operation is assumed). The probability that $n$ interfering pulses with repetition frequency $PRF_i$ fall into the interval $T_{\text{over}}$ is a Poisson law:

$$p_i(n) = \frac{(PRF_i \cdot T_{\text{over}})^n}{n!} e^{-PRF_i T_{\text{over}}} \quad (6)$$

Supposing that in an ideal condition (no noise, no clutter) the “single hit” probability of detection $p_d$ is very close to 1, then in the presence of $N_i$ interfering pulses, $p_d$ decreases as:

$$p_d(N_i) = \prod_{i=1}^{N_i} p_i(n = 0) = \exp \left[ - \sum_{i=1}^{N_i} PRF_i \cdot T_{\text{over}} \right] \quad (7)$$

Supposing that all interfering ships are solid state type with the same duty cycle ($d_i$), $PRF_i = 1000$ Hz and $\tau$ is variable from 10 μs to 100 μs ($d_i$ up to 10 %), while for the magnetron radar $\tau = 0.05 \mu s$, eqn. (7) when $N_i < 40$ can be simplified as:

$$p_d(N_i) \approx \exp [- \alpha \cdot N_i \cdot d_i] \quad (8)$$

with $\alpha = 1$ when the victim radar is a magnetron type, and $\alpha = 2$ when the victim is a solid state type. Fig. 3 and Fig. 4 show the reduction of the probability of detection, $p_d(N_i)$, when the victim radar is of a magnetron type and of a solid state one, respectively. The number of the interfering ships is: $N_i = 2, 5, 10, 15, 20$. The axis on the right represents the percentage of interference. We define the “probability of interference” $P_{\text{int}}$ as the probability of at least one interfering pulse in the interval $T_{\text{over}}$, i.e. the complement to 1 of eqn. (8). It is clear from these results that a few interfering ships, also with a low duty cycle, drastically reduce $p_d$ under the IMO limit of 0.8, especially when the victim is a solid state radar as shown in Fig. 4.

Fig. 3. Probability of detection $p_d(N_i)$ (left axis) and probability of interference $P_{\text{int}}$ (right axis) versus the solid state duty cycle, varying the number of interfering ships. Victim is a magnetron radar, interfering ships are all of the solid state type, $p_d(0) = 1$.

Fig. 4. Probability of detection $p_d(N_i)$ (left axis) and probability of interference $P_{\text{int}}$ (right axis) versus the solid state duty cycle, varying the number of interfering ships. Both victim and interfering radars are of the same solid state type (and parameters), $p_d(0) = 1$. **PD** indicates the pulse repetition frequency.
However in eqns. (7) and (8) we have supposed that all marine radars (both victim and interfering) transmit at the same frequency. Table III shows for magnetron radars a band of 9410 MHz ±30 MHz (practically implemented by all manufacturers, the “historical” band of 9375 MHz being less and less used), while for solid state radar the extent of use of the band from 9300 to 9500 MHz depends on the manufacturers. A first example i.e. a solid state marine radar on the civil ships market uses a transmitted peak power of 25 W, occupying circa 100 MHz of band for the six pulses with different chirp lengths (short, medium, long), a central frequency and a band occupancy (in MHz) of: 9410 – 9470 MHz (±2), 9466 – 9486 MHz (±4.7), 9486 – 9490 MHz (±1). A second example of a radar on the market (a VTS radar) shows a transmitted peak power of 200 W, with the central frequencies that can vary from 9166 MHz to 9465 MHz with 35 MHz of band for long (40 µs), medium (15 µs) and short (150 ns) chirp length. A detailed description of the measured signal characteristics of marine radar can be found in [18], [19]. Concluding, each of these new solid-state marine (or VTS) radar tends to occupy the whole marine band. In one case, the installation of two radar sets on a leisure boat apparatus) and to reduce the mutual interferences among the solid state radars. The improvement in terms of duty cycle corresponds to the number of sub-bands in which the total allocated band for marine radar (200 MHz) is divided.

Note that probabilities in Fig. 3 and Fig. 4 do not include the effect of the azimuthal integration of pulses (i.e. the extractor), which will be discussed in the next Section. Moreover, it has to be reminded that the “raw” assumption was made that any interfering pulse “blanks” the overlapped valid pulse.

VII. AZIMUTHAL INTEGRATION OF PULSES

The main antenna parameters for marine radar (excluding the long-range, coastal VTS radar) are shown in Table IV. The –3 dB azimuth beamwidth $\theta_{az}$ (degrees) and the rotation speed $\omega$ (rpm) permit to evaluate the dwell time: $t_d = \frac{\theta_{az} (\text{rpm})}{\omega}$ s.

With the operational value of the PRF, the number of azimuthal pulses available for integration is $N = \text{PRF} \cdot t_0$. Considering the range for $\theta_{az}$, $\omega$ and PRF, this number can vary from a few units to some tens (i.e. in most cases $N$ ranges from 5 to 30 pulses).

| TABLE IV. MAIN ANTENNA PARAMETERS FOR MARINE RADAR |
|-----------------------------|-----------------------------|
| ANTELLNA LENGTH | 4 ft (1.22 m), 6 ft (1.83 m), 8 ft (2.44 m) |
| $\theta_{az}$ (-3 dB) | 1.8°, 1.2°, 0.9° |
| $\theta_{az}$ (-3 dB) | 20° ± 24° |
| Rotation speed $\omega$ | 24/48 rpm |

A. Binary Moving Window Extractor

The video integration is implemented in digital form using an A/D converter after the envelope detector. For the evaluations, we consider the simple case (widely used in the past for its ease of implementation) of a 1-bit converter, leading to a closed-form expression, i.e. the Binomial law, [12]. It corresponds to a threshold detector operating directly on the output of the envelope detector, followed by an accumulator which counts up to $M$ “hits” out of $N$ before generating an output alarm. This is the well-known binary Moving Window, MW extractor [12]. In the case of noise alone the single hit probability of false alarm, $p_{fa}$ (written in lowercase), at the input of the extractor, is:

$$p_{fa} = \exp \left[ -\frac{T^2}{2} \right]$$

where the threshold $T$ has been supposed normalized to the rms noise values. Then the relationship between $N$, the detection
thresholds (i.e. the primary, \( T \), and the secondary, \( M \)) and the probability of false alarm at the output of the extractor, \( P_{FA} \) (written in uppercase), is (Binomial law):

\[
P_{FA} = \sum_{k=M}^{N} \binom{N}{k} p_{fa}^k \cdot (1 - p_{fa})^{N-k} \quad (12)
\]

For each \( M \), fixing \( P_{FA} \), for example \( 10^{-6} \), the probability \( P_{FA} \) is evaluated by eqn. (12) and the threshold \( T \) is estimated inverting eqn. (11). In the case of signal plus noise, the probability of detection on single hit, \( p_d \) (written in lowercase), depends on the target model. For a non-fluctuating (steady) target with a given Signal-to-Noise-Ratio, SNR, it is [6]:

\[
p_d = \int_{T}^{+\infty} v \cdot \exp \left[ -\frac{v^2}{2} - \text{SNR} \right] I_0(\sqrt{2\text{SNR}})dv \quad (13)
\]

where \( I_0(\cdot) \) is the modified Bessel function of the first kind. At the output of the extractor the probability of detection, \( P_D \) (in uppercase), is given by:

\[
P_D = \sum_{k=M}^{N} \binom{N}{k} p_d^k \cdot (1 - p_d)^{N-k} \quad (14)
\]

The optimum threshold \( M \) is chosen by minimizing the SNR with fixed \( P_{FA} \) and \( P_D \). Of course this way of integrating pulses causes losses with respect to a perfect (coherent) integrator exploiting the full dynamic range. For a steady target, \( P_D = 0.9 \) and a \( P_{FA} = 10^{-6} \). Table V shows the integration losses in addition to the coherent integration ones (data are obtained from [13] p. 65, fig. 2.9).

<table>
<thead>
<tr>
<th>Integration Loss (dB)</th>
<th>N</th>
<th>A-Video</th>
<th>B-MW</th>
<th>B – A</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>1.9</td>
<td>3.4</td>
<td>1.5</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>2.9</td>
<td>4.5</td>
<td>1.6</td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>3.5</td>
<td>5.1</td>
<td>1.6</td>
<td></td>
</tr>
</tbody>
</table>

The use of only 1-bit introduces an extra loss of \(-1.6 \pm 1.5\) dB (see the last column in Table V), which may be accepted because 1-bit A/D conversion offers significant protection against interference from random pulses of large amplitude. In fact, no matter how large the interfering pulse is, it can only add "1" to the count of first-threshold crossings.

It has been shown in [12] that the optimum threshold \( M \) (which minimizes the Signal to Noise Ratio, SNR), for a number of pulses of 10, 20 and 30 is \( M_{opt} = 6, 10, 14 \) respectively. For \( N = 20 \), \( M_{opt} = 10 \) and steady target, the single hit probability of detection \( P_d \) and the probability of false alarm \( P_{fa} \) are 0.62 (0.72) and 0.0806 when \( P_D = 0.90 \) (0.99) and \( P_{FA} = 10^{-6} \) respectively.

The probability \( p_d \) in eqn. (13) should be not be less than the previous values, but with interference, i.e. \( P_{Int} > 0 \), the \( p_d \) values decrease reducing the \( P_D \) and bringing it below the IMO requirement of 0.8 also for low probability of interference (less than 25 %) as shown in Fig. 6 (solid line).

Substituting in eqn. (8) the probability \( p_d(N_t) \) with \( 1 - P_{Int} \) and inverting this relationship, i.e.:

\[
d_i = -\frac{1}{a \cdot N_t} \ln(1 - P_{Int}) \quad (13)
\]

reading in Fig. 5 the values of \( P_{Int} \) when \( P_D \) reaches 0.8, by eqn. (13) the maximum duty cycle tolerable can be evaluated as shown in Table VI when the victim and interfering radars are a solid state type, \( a = 2 \) in eqn. (13). The values in Table VI take into account the improvement due to a future, desirable use of the different four bands shown in Fig. 5. When the victim is a magnetron radar, \( a = 1 \) in eqn. (13) and the duty cycle doubles. Without this “ideal” band allocation, the \( N_t \) values in Table VI must be divided by four assuming the full present use of the spectrum. For example, in the marine traffic situation of the gulf of Naples, Table II, where the 50th percentile (close to the mean value) of the number of ships in visibility is \( N_t = 12.5 \), assuming a duty cycle of 0.10 (Table III), using eqn. (10) we get \( P_{Int} = 0.54 \), i.e. \( P_{Int} = 0.46 \), corresponds to a negligible (nearly zero) probability of detection \( P_D \), even with the “ideal” band allocation (eq. (10)).

![Fig. 6. Probability of detection after integration versus the probability of interference for \( N = 20 \), \( M = 10 \). (Non-fluctuating target).](image)

| MW: \( N = 20, M = 10 \), “victim” SS, “interfering” SS |
|------------------|------------------|------------------|------------------|------------------|
| \( P_D(N_t = 0) \) | \( N_t = 5 \)     | \( N_t = 10 \)    | \( N_t = 15 \)    | \( N_t = 20 \)    |
| 0.90            | 3.36 %           | 1.68 %           | 1.12 %           | 0.84 %           |
| 0.99            | 9.44 %           | 4.72 %           | 3.16 %           | 2.36 %           |

It can be concluded that the presence of interferences from marine solid state radars, also with low probability, strongly reduces the probability of detection when most vessels will use those solid state radars, unless their duty cycle is kept low and bands are suitable allocated. A maximum duty cycle of 2 % in moderate traffic as the sea area near Naples, see Table II and second row of Table VI (\( N_t = 10 \)), may be suggested with the allocation shown in Fig. 5, to be reduced to 0.5 % without such a coordinated allocation.
VIII. COMMENTS AND CONCLUSIONS

The effects of interfering radar signals on the detection performance of solid state or magnetron marine (navigation) radars depend on many variables difficult to model, mainly related to the environment and to the specific conditions of the vessel traffic [14], [20].

In this study we limited ourselves to consider the presence of interfering radar pulses (Poisson process) assuming that they simply negate the radar detection of overlapped, valid echo pulses, with no increase of the false alarm probability. This operation is typical of the widely used “interference blanking circuit” implementing a logical AND between successive radar sweeps. With such a model, the effect on the “victim” depends only on temporal considerations (pulse-width and PRF) and the probability of interference is related to the number of vessels in radar visibility, to the PRF and to the sum of the pulse-widths (interfered and interfering). The overall driving factor is the integrated duty cycle of the radars in the visibility area of the “victim” radar, as well as its pulse-width.

The analysis has shown that the increasing diffusion of the solid state marine radars could represent a critical and relevant problem for the sea traffic when the percentage of operating solid state radars will reach a few percent, confirming what was reported seven years ago in [5].

As a matter of fact, while in marine magnetron radars (having a duty cycle less than $10^{-3}$) the mutual interference can be easily managed using simple techniques as the above-referenced “logic AND” canceller, in solid state marine radars (whose duty cycle is of the order of 5% to 20%) such a canceller strongly reduces the detection probability.

Pertaining solutions are not easily found. In the general radar (and radio communications) context, the interference problem is dealt with by diversity in one or more parameters: frequency, space, time, polarization, code. For the problem at hand, the limited (200 MHz) allocated band, associated with the relatively wide band of the high-resolution and short-range operating modes, and with the present lack of coordination between vessels concerning radar operation, show a limited potential for frequency multiplexing. The same applies of course to the emission time. Concerning the space parameter, the usage of ultra-low sidelobes antennae could limit interferences to the main lobe, but the cost of these antennae is likely out of the budget of the marine market. Polarization diversity only permits to radiate pairs of orthogonal signals, and the same applies to Up and Down Chirp codes, while the traffic analysis presented before underlines the need here for N-plies (with $N >> 1$, order of tens), not pairs, of orthogonal signals.

Noise radar technology is a way being investigated to try to mitigate the problem presented in this paper, see [15], [16] and [17]. However, the related costs are probably beyond the affordable costs for simple radar sets on board of fishing or leisure boats, therefore have to be found some simpler solutions.

Finally, the results shown here will be refined in future studies adding a more complete model of the “victim” radar receiver, the antenna patterns and the multipath effects. Such studies could lead to suggest new regulations (e.g. posing a duty-cycle limit) and new architectures for the next generation marine radars.

ACKNOWLEDGMENT

Special thanks to C.V. Giuseppe Aulicino and to S.T.V. Antonio Vollero of the Italian Coast Guard for their collaboration and for providing AIS data of vessel traffic.

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