Measurement 122 (2018) 186–191

Contents lists available at ScienceDirect

Measurement

journal homepage: www.elsevier.com/locate/measurement

Measurement of radar horizon in a real marine environment and its influence on the reduction of interferences

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ARTICLE INFO

Keywords:
Detection
Range
Radar horizon
Interferences
GSM mobile telephony

ABSTRACT

Coastal electromagnetic environment is increasingly complex. The emergence of cellular telephony provides important spectrum occupancy at 900 MHz frequency band. Radar systems are essential tools for the detection of targets at the sea, and in a tactical scenario nearby onshore, it is extremely important that they remain unaffected by the existent electromagnetic pollution. Despite most radar systems operate at frequency ranges from 2 GHz to 40 GHz, low-frequency radars at ultra-high frequencies might fall within GSM/GPRS 900 MHz frequency band, where the cellular network generates a strong interference and a desensitization of the radar by the external noise produced by the coastal base-stations. This work shows that the approximate limit of these mutual interferences is the radar horizon, analyses the degradation in terms of probability of detection and range performance, and demonstrates how radar horizon can be used as a reference to mitigate such interferences. The analysis presented herein is based on a real measurement campaign carried out at Cádiz Bay, Spain.

1. Introduction

With the rise of wireless communications, the electromagnetic environment has become extremely complex. In the last decades, the increase of electromagnetic emissions hinders the electromagnetic compatibility among existing radiofrequency systems. This problem is especially remarkable in coastal areas, where ground-based emitters might interfere with on-board systems on ships and with all the sensors used for maritime traffic control. Among them, radar systems play an important role, due to their high transmission power.

The problem at hand is complex to deal with because, on the one hand, cellular telephony has become one of the most important emerging systems. These communication networks are quickly expanding their coverage by adding new frequency bands to their spectrum, while increasing the number of terrestrial base stations. Main mobile telephony providers tend to extend their influence a certain radius over the sea, nearby onshore, to provide the quality of service required in urban coastal areas, and thus, unavoidably, the electromagnetic complexity is also transferred to the adjacent coastal waters.

On the other hand, radar systems are fundamental elements in vessels. They constitute the main safety sensors in navigation, providing information of the surrounding environment under any climate conditions. For warships, such systems are even more important, since they allow the control of tactical scenarios, both for aerial and surface targets, so radar systems are a fundamental part in the proper development of any operation.

Operations in coastal waters, denoted as low-intensity scenarios [1], are nowadays increasingly common, and thus, the importance of the electromagnetic environment nearby the shore and the possible interferences that might exist become more important than ever. This is why the horizon radar, a well-known concept, is essential to analyse the mitigation of the signal produced onshore that might represent the source of interferences of the systems on-board.

This paper evaluates the effective interferences created by coastal electromagnetic pollution on a radar system on-board a vessel, and quantifies the ability of the radar horizon to mitigate them.

The work is structured as follows: firstly, theoretical concepts on radar horizon and radar sensitiveness will be introduced. Secondly, we will demonstrate how the radar horizon is able to mitigate the interferences nearby the shore, defining an operative upper limit for the detection range. Finally, an analysis of the degradation on the probability of detection and range coverage is conducted, summarizing this study in the conclusion section.

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https://doi.org/10.1016/j.measurement.2018.03.031
Received 5 September 2017; Received in revised form 17 February 2018; Accepted 13 March 2018
Available online 15 March 2018
0263-2241/

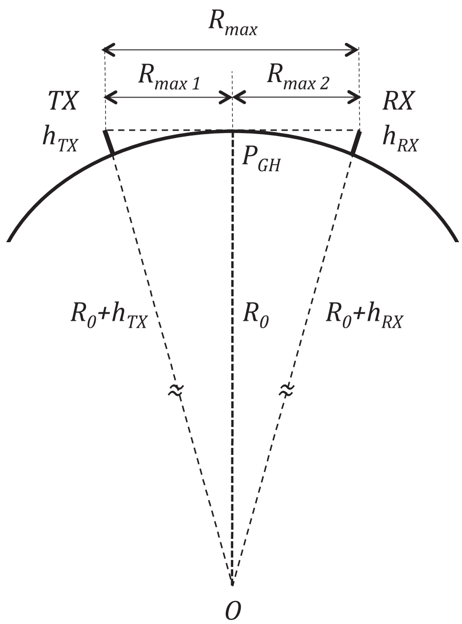

Fig. 1. Geometrical horizon (P_{GH}) and maximum horizon range ($R_{\max}$).

2. Theoretical background

2.1. Radar horizon range

For frequencies above 300 MHz (Ultra-High Frequencies or UHF) electromagnetic waves propagate linearly, and therefore, terrain and/or sea surface will usually block the radar line-of-sight (LOS). The maximum radar range achievable under these circumstances is known as the *radar horizon range* ($R_{\max}$) and is limited by the geometrical horizon (P_{GH}) and the height of transmitter and receiver antennas (h_{TX} and h_{RX} respectively). Fig. 1 depicts this scenario, where R_0 is the Earth's radius (6.371 km).

Under these conditions, the radar horizon range ($R_{\max}$), which is the maximum distance where a radar target can be detected, is given by (1):

$$R_{\max} = R_{\max\,1} + R_{\max\,2} \tag{1}$$

where R_{max1} is the distance between the transmitter (*TX*) and the point of the geometrical horizon (P_{GH}), and R_{max2} is the distance between the geometrical horizon (P_{GH}) and the receiver (*RX*). Applying trigonometric relationships, and assuming that $2h_{TX}R_0 \gg h_{TX}^2$ and $2h_{RX}R_0 \gg h_{RX}^2$, the expression for the radar horizon range ($R_{\max}$) can be reduced to (2), with all magnitudes measured in meters:

$$R_{\max} = \sqrt{2\cdot h_{TX}\cdot R_0} + \sqrt{2\cdot h_{RX}\cdot R_0} \tag{2}$$

However, due to the decrease of the air diffraction coefficient with height, electromagnetic waves tend to bend over the Earth's surface [2], reaching larger distances than the $R_{\max}$ defined in (2), as shown in Fig. 2.

For radar altitudes lower than 10 km, as the study herein presented, this effect can be modelled using the 4/3 Earth model in (3) which applies an *effective earth's radius* (R_e) instead of the real one (R_0) [3]. This effective radius (R_e) will be the one used in this work for the analysis of the radar horizon.

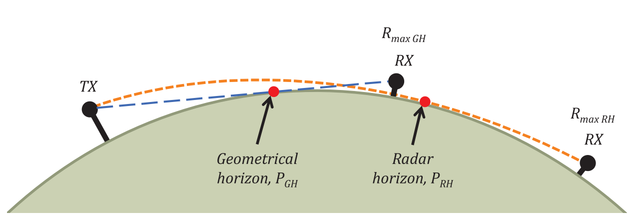

Fig. 2. Geometrical radar horizon ($R_{\max\,GH}$), vs. real radar horizon range ($R_{\max\,RH}$).

$$\frac{R_e}{R_0} = \frac{4}{3} \tag{3}$$

For maritime environments, $R_{\max}$ in (2) is usually expressed in terms of nautical miles (*nm*), so that the resulting expression for the radar horizon range, using the 4/3 Earth model, can be approximated accurately as follows:

$$R_{\max}\ (\text{nm}) \cong 2.22\cdot(\sqrt{h_{TX}} + \sqrt{h_{RX}}) \tag{4}$$

with h_{TX} and h_{RX} expressed in meters.

2.2. Radar sensitiveness

The sensitiveness of a radar receiver refers to the ability of a system to discriminate distant or small targets (in terms of their radar reflectivity) among the noise. It represents the minimum signal power reflected by a particular target that should reach the radar receiver to make a proper detection. The relationship between the radar range and the sensitiveness is defined by the radar equation in (5), where sensitiveness appears in the denominator as $S_{\min}$ [3]:

$$R_{\max} = \sqrt[4]{\frac{P_T\cdot G^2\cdot\sigma\cdot\lambda^2}{(4\pi)^3\cdot L\cdot S_{\min}}} \cong \frac{k_R}{\sqrt[4]{S_{\min}}} \tag{5}$$

The rest of parameters in (5) are the transmitted power (P_T), the antenna gain (*G*, squared in case of monostatic radars), the *Radar Cross Section* or reflectivity of the target (σ or *RCS*), the wavelength corresponding to the operating frequency (λ) and the system losses (*L*). For the sake of this study, we will merge all predefined parameters besides $S_{\min}$ in a constant (k_R) to highlight the importance of the sensitiveness in the radar coverage.

Sensitiveness $S_{\min}$ cannot be interpreted as an absolute value because it is relative to the noise of the system. Fig. 3 shows how the same $S_{\min}$ can lead to a proper detection with low probability of false alarms (Fig. 3(a)), whenever the noise of the system is several *dB* below the radar threshold. However, the same $S_{\min}$ and target echo do not warrantee a proper detection because under high-noise conditions, as in Fig. 3(b), the probability of the noise surpassing the threshold increases, and so do the number of false alarms, degrading the radar reliability and performance.

Therefore, the sensitiveness of a radar is commonly defined in terms of the signal-to-noise ratio (S/N or *SNR*) following (6):

$$S_{\min} = K\cdot T\cdot B\cdot F\cdot\frac{1}{G_p}\cdot(S/N)_{\min} \cong k_S\cdot SNR_{\min} \tag{6}$$

where *K* is the Boltzmann's constant, *T* refers to the internal temperature of the system in *Kelvin*, *B* is the bandwidth in Hz, *F* is the noise figure and G_P is the processing gain of the radar.

As Fig. 3 shows, the system will trigger a proper detection whenever the power received from both the target or the noise surpasses a certain threshold determined by the radar sensitiveness ($S_{\min}$). To provide a reliable detection, the *SNR* of the system must ensure a low probability of false alarms, so the sensitiveness ($S_{\min}$) defines the minimum value required for the *SNR*, denoted as $(S/N)_{\min}$ or $SNR_{\min}$. The $SNR_{\min}$ of a system will then determine the probability of detection (P_D) and the probability of false alarm (P_{FA}) of the radar, whose relationship can be accurately approximated by (7), where *erfc* is the *complementary error function* in (8) [4].

$$P_D = 0.5 \times erfc\left(\sqrt{-\ln(P_{FA})} - \sqrt{SNR + 0.5}\right) \tag{7}$$

$$erfc(\alpha) = 1 - \frac{2}{\sqrt{\pi}}\int_0^{\alpha} e^{-v^2} \tag{8}$$

Eq. (5) can be rewritten in terms of $SNR_{\min}$, merging constants k_R and k_S into k_{RS}, so the dependency of the radar range by means of the sensitiveness remains clearer: