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Ultra-High Frequency Passive Radar Coverage for Cars Detection in Semi-Urban Scenarios

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***Abstract*—**A study of achievable coverages using passive radar systems in terrestrial traffic monitoring applications is presented. The study includes the estimation of the bistatic radar cross section of different commercial vehicle models that provide challenging low values which make detection really difficult. A semi-urban scenario is selected to evaluate the impact of excess propagation losses generated by an irregular relief. A bistatic passive radar exploiting UHF frequencies radiated by digital video broadcasting transmitters is assumed. A general method of coverage estimation using electromagnetic simulators in combination with estimated car average bistatic radar cross section is applied. In order to reduce the computational cost, hybrid solution is implemented, assuming free space for the target-receiver path but estimating the excess propagation losses for the transmitter-target one.

***Keywords*—**Bistatic radar cross section, passive radar, propagation losses, radar coverage.

I. Introduction

URBAN traffic monitoring is a task of great importance, especially in smart cities [1]. Control and security tools are required for the detection and tracking of terrestrial vehicles for traffic regulation purposes, acquisition of statistical data, or surveillance applications. Conventional active radar systems have been widely used. These systems provide their own illumination and, with a correct choice of the working frequency, can be insensitive to weather conditions; but they must fulfill legislation requirements on electromagnetic emissions and are usually characterized by high design, development and maintenance costs, mainly related to their dedicated transmitter.

Passive radars are emerging technologies that are awaking great interest due to the absence of a dedicated transmitter. They can be defined as a set of radar techniques that use non-cooperative signals, such as broadcast, communications, radar, or radio-navigation signals, as illumination sources named Illuminators of Opportunity (IoO) [2]. These techniques try to overcome the aforementioned active radar drawbacks without a significant detection capabilities reduction. The relevance of these systems is proved by the great number of available publications, especially related with the exploitation of digital broadcasting systems: Digital Audio Broadcasting (DAB) [3], Digital Radio Mondiale (DRM) [4], Global System for Mobile Communications (GSM), UMTS or Universal Mobile Telecommunications System [5], [6], and Digital Video Broadcasting-Terrestrial (DVB-T) [7]-[10].

DVB-T transmitters are really a promising option for the terrestrial traffic monitoring, taking into consideration the specific requirements that this kind of systems could arise [9]-[11]. Because of that, they are selected as IoOs in the present paper whose main objective is the study of achievable coverages in semi-urban scenarios where the influence of non-uniform reliefs on propagation losses cannot be ignored. The analysis is completed with the characterization of the bistatic radar cross section (BRCS) of different car models, the assumption of a minimum signal power required at the input of the system receiver, and the estimation of the system propagation losses.

The rest of the paper is organized as follows: In Section II, the problem of the estimation of passive radar systems coverages is considered, focusing on the detection of cars in semi-urban scenarios, by means of the modeling of the BRCS of different cars models, the calculus of the excess propagation losses, and the required minimum received signal power. In Section III, an approximated coverage calculation methodology is presented, and the obtained coverage results for a given radar scenario are shown. Finally, the main conclusions are presented in Section IV.

II. Passive Radar Coverage Estimation Problem

The basic geometry of a Passive Bistatic Radar (PBR) is presented in Fig. 1.

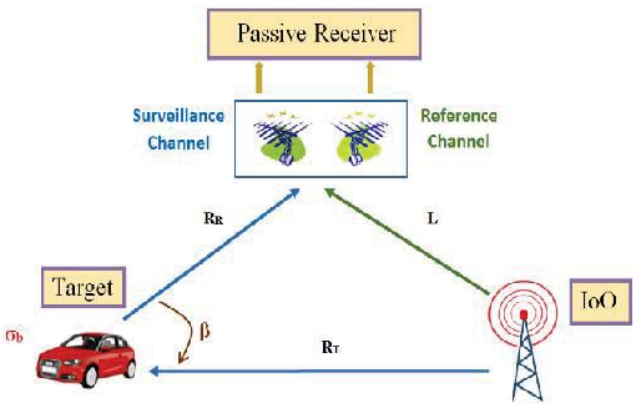

Fig. 1 Basic PBR geometry

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A dual channel reception system is required: a surveillance channel for targets echoes acquisition, and a reference one, for acquiring the IoO signal. Target echoes signals will be correlated with Doppler shifted copies of the reference signal to generate the Cross-Ambiguity Function, CAF, which will provide a processing gain that depends on the signal length, and the capability to estimate the bistatic range and Doppler of the detected targets.

The key tool for estimating the PBR coverage is the bistatic radar equation (1):

$$\left(R_R R_T\right)^2 = \frac{p_T g_T g_R \lambda^2 \sigma_b}{\left(4\pi\right)^3 p_R} \cdot l_{IoO-target} \cdot l_{target\text{-}BPR} \quad (1)$$

where R_R and R_T are the distances between the target and the passive receiver and the IoO, respectively, $l_{target\text{-}PBR}$ and $l_{IoO\text{-}target}$ are the excess propagation losses associated to both paths; p_T and g_T are the power and antenna gain of the IoO, g_R is the PBR receiver antenna gain; p_R is the available power at the receiver, and σ_b is the target BRCS.

Under the free space propagation conditions ($l_{IoO\text{-}target}=l_{target\text{-}PBR}=1$), given a minimum value of p_R (sensitivity), a Cassini oval is obtained, that is widely used as a first approach for coverage calculations. More precise coverage estimations require three basic elements that are analyzed in the following subsections: a proper model of target BRCS, determination of system sensitivity, and proper models for $l_{IoO\text{-}target}$ and $l_{target\text{-}PBR}$.

A. Estimation and Analysis of BRCS of Different Cars Models

The POFACETS software (Naval Postgraduate School, California), has been used for modeling the BRCS of three commercial cars, assuming they are all made of Aluminum (Table I and Fig. 2), and a selected radar scenario that stablishes the relative position of the target with respect to the system elements (bistatic geometry).

In Table II, the estimated BRCSs for a working frequency of 600 MHz and horizontal polarization were summarized. The selected semi-urban scenario was located on campus of the University of Alcala, where the passive radar demonstrator IDEPAR [9], [10], developed by Signal Theory and Communication department, was placed (Fig. 3).

TABLE I
COMMERCIAL CARS SELECTED FOR THE BRCS STUDY

Feature	Audi A5	Mazda 6 sport	Peugeot 307
Length	4.625 m	4.735 m	4.211 m
Width	1.855 m	1.795 m	1.757 m
Height	1.370 m	1.440 m	1.509 m

Two different methodologies were considered:

1) Global analysis: Grazing incidence and observation angles are fixed and equal to 89.2º and 89.8º, respectively, azimuth incidence angles varied from 0 to 180º in steps of 20º. For each azimuth incidence angle, the azimuth observation one was varied from 0 to 360º in steps of 0.5º.

In Fig. 4, the estimated two-dimensional BRCS maps are depicted for the three vehicle models.

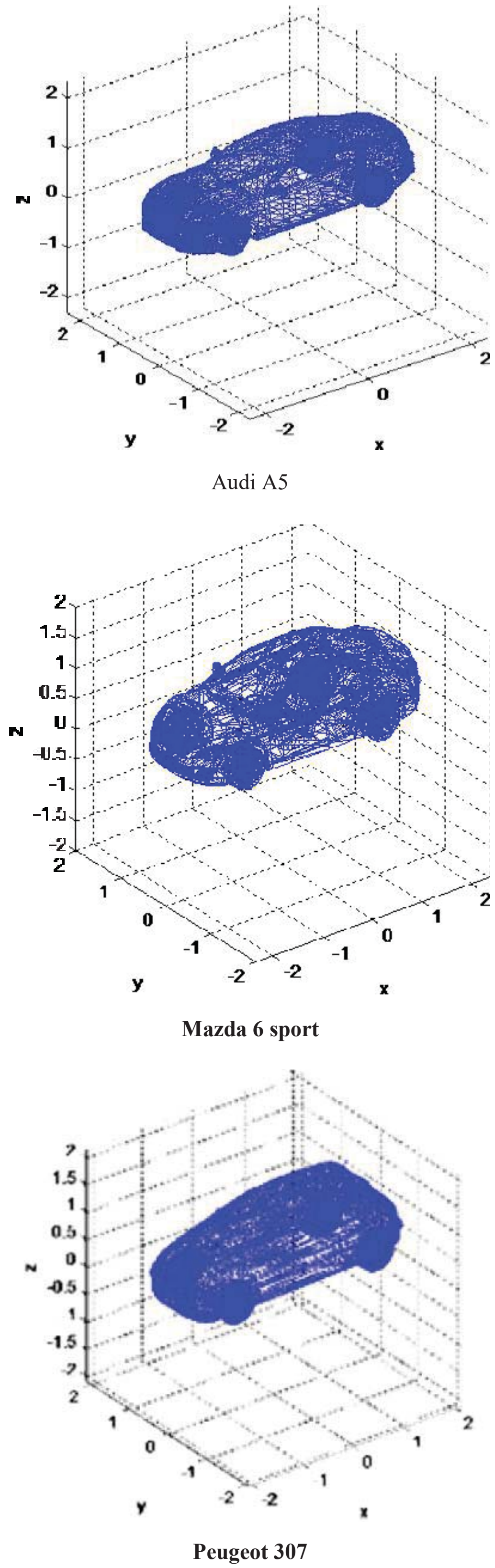


Fig. 2 Commercial cars models used in Pofactes

2) Bistatic angle dependent analysis: Grazing angles stay the same as in previous method, but making the relation between incidence and observation azimuth angle, the bistatic angle, constant. Values of β = {60º, 90º, 120º} were considered for the area of interest associated to the selected scenario. For each bistatic angle, the target was completely rotated.

For the coverage studies carried out in this work, the conservative value of -0.365 dBsm, as the average value for the three results obtained by using the second method, has been selected.

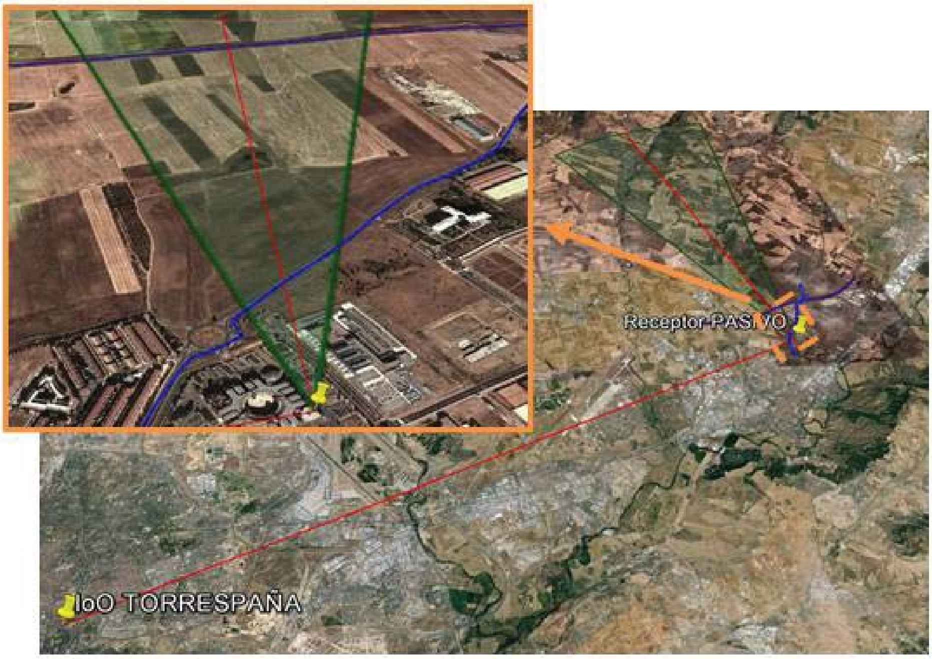


Fig. 3 Detail of the PBR location in the Campus of the University of Alcalá

TABLE II
COMMERCIAL CARS SELECTED FOR THE BRCS STUDY

BRCS (dBsm)	Audi A5			Mazda 6 sport			Peugeot 307		
	Max.	Min.	Average	Max.	Min.	Average	Max.	Min.	Average
Global	29,382	-6,985	10,748	27,176	-11,02	9,194	36,887	-9,982	12,883
β = 60º	6,48	-43,19	-2,742	-3,525	-30,678	-5,118	3,529	-33,963	-7,188
β = 90º	9,21	-33,089	0,881	4,877	-26,29	-2,489	7,296	-35,618	-2,597
β = 120º	12,44	-29,18	4,941	8,851	-41,254	-1,187	8,278	-27,619	-0,142

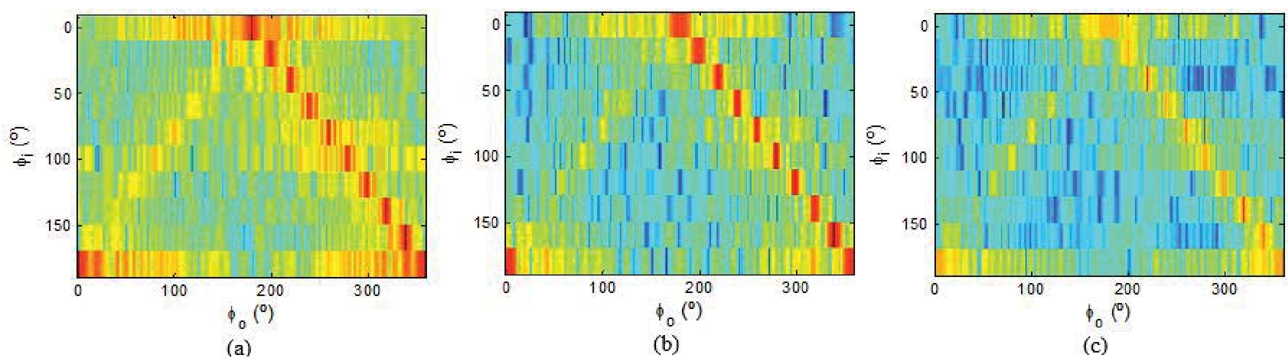


Fig. 4 2D BRCS maps for three representative vehicle models: (a) Audi5, (b) Mazda 6 sport and (c) Peugeot 307

B. System Sensitivity

System coverage is defined for the specific target and interference models, as the maximum range where a target is detected fulfilling Probability of Detection, P_D, and Probability of False Alarm, P_{FA}, requirements. For a squared law detector in a noise dominated environment, the detection curves for Swerling I models and a $P_{FA} = 10^{-6}$ are presented in Fig. 5 (SNR_{DET} is the Signal-to-Noise Ratio at the detector input) [8]. For P_D=80%, and P_{FA} =10^{-6}, a SNR_{DET} of 21 dB is required.

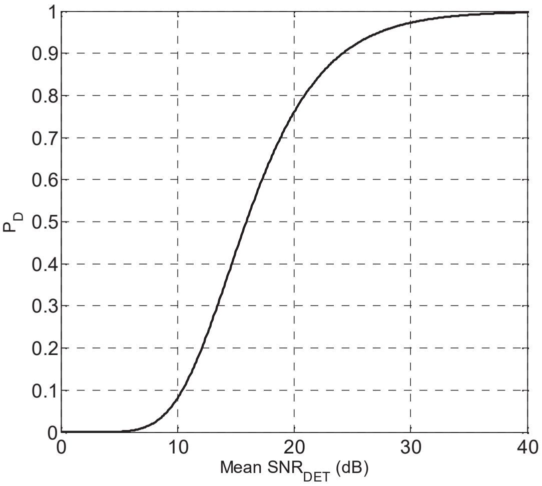


Fig. 5 Detection curve for a squared law detector and Swerling I targets in a noise dominated environment. P_{FA}=10^{-6}

For SNR_{DET}=21 dB, typical system sensitivity values have been estimated by using noise factors, gains and losses in PBR receiving chains based on commercial acquisition boards such as National Instruments USRP devices [12]. As a result, values ranging from -140 dBm to -150 dBm have been obtained.

C. Excess Propagation Losses

The modeling of excess propagation losses is usually carried out using electromagnetic simulators. In this work, WinProp (AWE Communications GmbH) was used.

This software allows the selection of different propagation models and the integration of GIS data in order to model the relief of the area of interest. Assuming the already commented radar scenario, the relief information is depicted in Fig. 6.

Torrespaña transmitter was selected as IoO due to its location, height, global coverage, and power signal. In Table III, the main features of the IoO and bistatic system parameters are summarized.

TABLE III
SCENARIO MAIN PARAMETERS

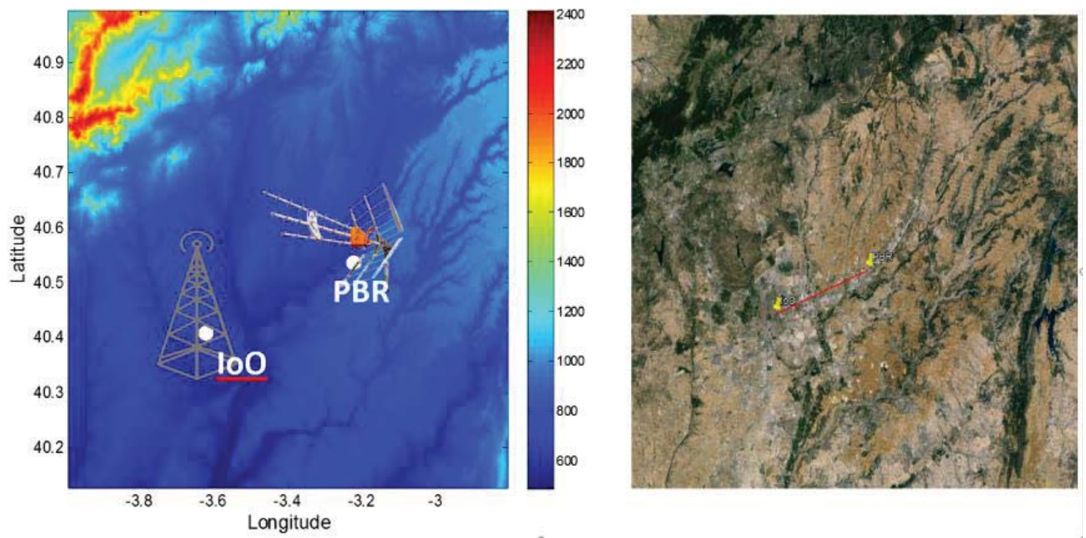
Scenario Features	Value
PBR Location	Longitude: 40º25′16.64″N Latitude: 3º39′51.39″W
IoO Location (*Torrespaña*)	Longitude: 40°30'47.19"N Latitude: 3°20'55.02"W
IoO ERP (Equivalent Radiated Power)	20 kW
IoO Working Frequency (DVB-T)	478 – 782 MHz
Base-Line (L)	28 km

The simulation of both system paths, IoO-Target and Target-PBR, is required in order to obtain an accurate estimation of the received echo signal power at the PBR receiver surveillance channel.

The available IoO power estimated by WinProp at each point of the defined area of interest, $p_{IoO\text{-}target}$ in (2), is depicted in Fig. 7. The target BRCS and the estimation of the excess propagation losses along the IoO-Target path were considered.

$$p_{IoO-target} = \frac{p_T g_T}{4\pi R_T^2}\frac{\lambda^2}{4\pi}\cdot l_{IoO-target} \qquad (2)$$

The estimation of the excess propagation losses along the target-PBR requires new estimations that overload the processing system, and an increased computational time. In the next section, an approximated method is proposed and evaluated.



(a) (b)

Fig. 6 Relief map (a), and selected area of interest (b)

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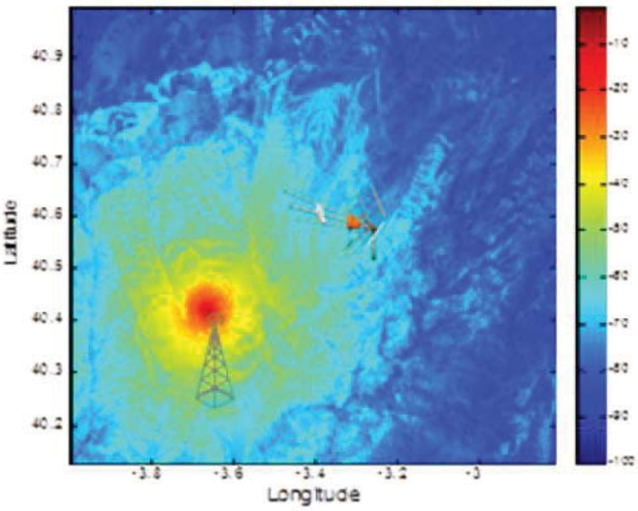

Fig. 7 IoO available power (dBm) at each point of the area of interest

III. Results

As an intermediate approach between the application of the simplest model, where the excess propagation losses are assumed $l_{IoO\text{-}target} = l_{target\text{-}PBR}$=1, and a complete model that estimates both losses, a hybrid solution is proposed by combining the estimated $l_{IoO\text{-}target}$, and free space losses for the target-PBR path.

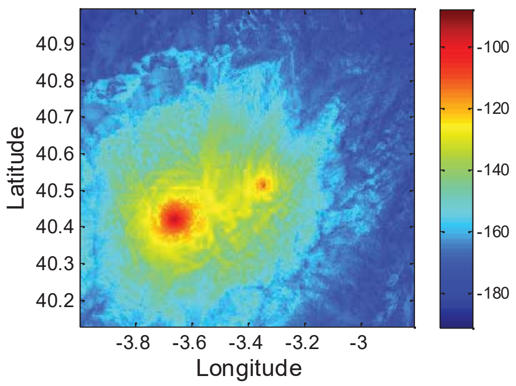

Fig. 8 Estimation of the power received at the PBR considering a car with BRCS equal to -0.365 dBsm, a g_R of 15 dB and $l_{target\text{-}PBR}$=1

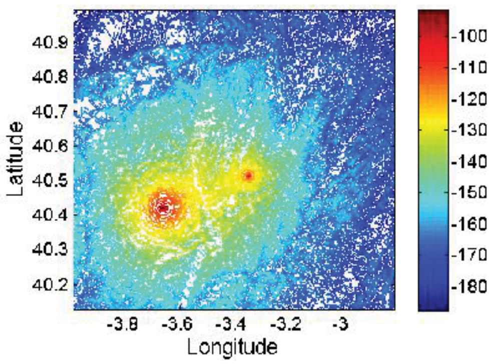

Fig. 9 Iso-power level at PBR receiver curves associated to Fig. 8

As a result, coverage areas are not the expected Cassini ovals due to the relief effect over the first path losses. The power received at the PBR considering a car with BRCS equal to -0.365 dBsm, and a receiving antenna gain of 15 dB, is represented in Fig. 8. The associated iso-power levels at PBR receiver curves are shown in Fig. 9.

The coverage masks for receiver sensitivities equal to -140 dBm and -150 dBm are depicted in Figs. 10 and 11 respectively. Signal level increases as the target approximates the IoO. This is an effect of the applied approximation: target locations closer to the IoO have a longer R_R distance, and the free space propagation model is assumed for a longer path, giving rise to a fictitious power level increases due to the unconsidered excess propagation losses. This effect is less important in target locations closer to the PBR, because in these points, R_R (Target-PBR path) giving rise to a comparatively lower estimation error due to the difference between free space and excess propagation losses. However, the non-uniform relief could modify this effect through local regions with high propagation altering conditions.

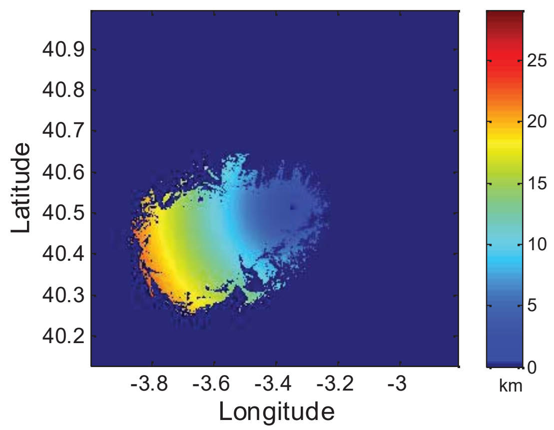

Fig. 10 Coverage mask for a sensitivity equal to -150dBm obtained using the approximated method

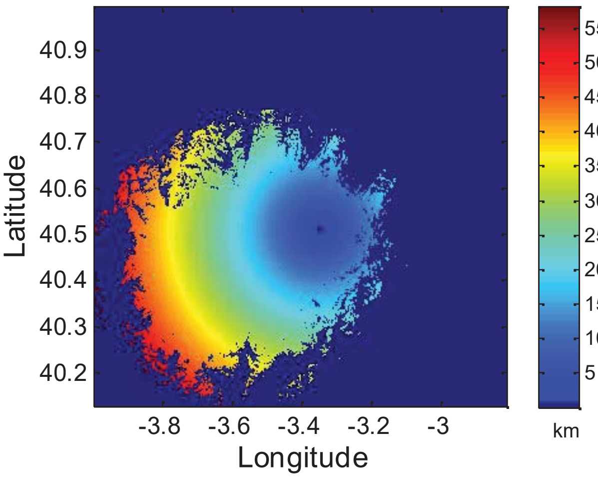

Fig. 11 Coverage mask for a sensitivity equal to -140dBm obtained using the approximated method

IV. Conclusion

The general problem of the estimation of passive radar coverage areas was considered in this work. The detection of terrestrial vehicles using UHF signals in the DVB-T frequency band was the defined case study. A semi-urban radar scenario was selected to evaluate the impact of irregular reliefs in the propagation losses.

Three key elements of the bistatic radar equation were analyzed: the excess propagation losses along IoO-target and target-IoO paths, the minimum signal level required at the receiver input, and the target bistatic RCS.

The estimation of maximum, minimum, and average BRCSs of three different commercial cars was carried out by taking into consideration two approaches: the first one assuming a global analysis, and the second one using fixed bistatic angles coherent with the region under study. The results revealed really low values combined with low Doppler shifts which will complicate detection tasks significantly.

A complete study of the excess propagation losses along the IoO-target path using an electromagnetic simulation, reveals a big deformation of the theoretical Cassini ovals. Due to the complexity of the estimation of the target-PBR path excess losses, the impact of assuming free space propagation along this path was analyzed. Results prove that the associated error depends on the scenario relief and on the considered target position, being lower for locations at lower distances from the receiver.

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