

VHF Coverage in the Azores archipelago using the Global Maritime Distress and Safety System

Frederico Neto, António Rodrigues, José Sanguino
 Instituto Superior Técnico, Av. Rovisco Pais, 1049-001, Lisbon, Portugal
 freisneto@tecnico.ulisboa.pt

Abstract—As Portugal is a coastal country and signatory to the SOLAS Convention, it has under its responsibility a maritime area of around 5 754 848 km² to control the safety of human life at sea. In order to ensure effective control, radio communications are an essential means as they allow, in case of need of a distress call, the immediate contact to maritime search and rescue centres which consecutively initiate the assistance process. With the purpose of verifying radio coverage in the VHF band of Portuguese Navy coastal stations located in the Azores archipelago, one used the ITU-R P.1546-6 Recommendation, which is a point-area prediction method for terrestrial services in the frequency band between 30 MHz and 4 000 MHz. In the present work, a correction to this Recommendation was included in order to adapt the accentuated losses due to radio signal diffraction caused by the terrain in the Azores archipelago.

Index Terms—GMDSS; Safety of life at sea; Azores archipelago; VHF; ITU-R P.1546; Radio coverage

I. INTRODUCTION

THE advent of radio communications was a fundamental element for the safety of human life at sea. The development of new technologies in radio communications has given conditions to International Maritime Organization (IMO), an organism concerned with the safety of navigation and the protection of the marine environment, and to the International Telecommunication Union (ITU), for the design of the new telecommunications system, which allows, wherever a ship is, to send and receive distress calls.

Despite transoceanic travel, world navigation activities still occur within 200 nautical miles (NM) of the coastline, most of which are within 40 NM, in addition to regional and local traffic, mainly fishing and recreational boats, international cruisers, cargo ships and tankers plan their itineraries as close to the coast as possible. The basis for choosing this route is naturally related to safety, but it will cause traffic congestion and eventually cause marine accidents. Europe has one of the highest concentrations of shipping and also includes several of the busiest shipping lanes in the world. Especially in the waters from Portugal to the European Atlantic Ocean, the amount of maritime traffic within the coast Line-of-Sight (LoS) is considerable [1].

The role of maritime Very High Frequency (VHF) communications in security and transportation services have been fully recognized and supported by national and international regulatory agencies. Since its establishment, all previous World Radiocommunication Conference (WRC) have made contributions to the adaptation of spectrum allocation, which

can adapt to the technological development in Maritime Mobile Service (MMS), thus greatly improving maritime communication capabilities.

The Portuguese Navy is responsible for an area of about 5 754 848 km² (equivalent to 62 times the area of the Portuguese national territory) [2] and must ensure that its services are efficient so that any accident on the open sea or near the coast triggers immediately the actions necessary for the process of search and rescue of human lives at sea.

As an example, between 1994 and 2020, the Maritime Rescue Coordination Centre (MRCC) Delgada, located in the Azores archipelago and responsible for the Search and Rescue Region (SRR) Santa Maria, was directly involved in 6896 Search and Rescue (SAR) cases and on the rescue of 2745 human lives in distress at sea.

In this paper, and taking to account the high sea traffic in the Azores archipelago and the importance of an efficient SAR service that guarantees a response from the responsible authorities as quickly as possible in order to safeguard human life at sea, a thorough search for possible shadow areas regarding the VHF coverage around the islands and, eventually an improvement of these systems, is then necessary. Section II will introduce the first steps in marine radio communications and the origin of the standardization of the global concept of search and rescue of human life at sea. It also describes the state of the art of Global Maritime Distress and Safety System (GMDSS) in order to better understand all the architecture and technology that this system is composed (focusing on the VHF Band). Section III describes the current system architecture of the Portuguese Navy VHF MMS and a simple VHF radio coverage map. Section IV presents the radio propagation models chosen to implement the calculation of the VHF coverage in the Azores archipelago which is described and demonstrated in Section V. Finally, Section VI gives the conclusions regarding the analysis of the results obtained in Section V.

II. GLOBAL MARITIME DISTRESS SAFETY SYSTEM CONCEPT

The first use of wireless in communicating the need for assistance came on 17 March 1899, the East Goodwin Sands Lightship sent a signal on behalf of the merchant vessel Elbe, which had run aground on the treacherous Goodwin Sands off the coast of Kent. On the 30th of April 1899 the same ship, East Goodwin Sands lightship was rammed in a fog in the early morning hours by the SS R. F. Matthews and send on

his behalf a distress call to a shore station at South Foreland and help was dispatched [3], [4].

In 1896, was granted the world's first patent for a system of wireless telegraphy [5] to the wireless pioneer Marconi that seeing that wireless would not compete with wire telegraphy for land-based communication, concentrated his efforts on ship-to-shore communications and therefore saw the commercial possibilities of equipping ships with wireless telegraph equipment [6]. In 1897 Marconi formed the Wireless Telegraph and Signal Co. Ltd, the first commercial development of this new technology in the world [6] and by December 1904, the Company had in operation some sixty nine land stations and one hundred and twenty four ship stations worldwide as tangible evidence of the growing appreciation of the value of wireless telegraphy as a medium of commercial and military communication [7].

A. SOLAS and SAR Conventions

The Safe of Life at Sea (SOLAS) Convention in its successive forms is generally regarded as the most important of all international treaties concerning the safety of merchant ships. The first version was adopted in 1914, in response to the Titanic disaster. The main objective of the SOLAS Convention is to specify minimum standards for the construction, equipment and operation of ships, compatible with their safety. The current SOLAS Convention includes Articles setting out general obligations, amendment procedure and so on, followed by an Annex divided into 14 Chapters [8]. Chapter IV - Radio communications of this Convention, incorporates the Global Maritime Distress and Safety System (GMDSS) concept. All passenger ships and all cargo ships of 300 gross tonnage and upwards on international voyages are required to carry equipment designed to improve the chances of rescue following an accident, including satellite Emergency Position Indicating Radio Beacon (EPIRB) and Search and Rescue Transponder (SART) for the location of the ship or survival craft [8].

The system, designated by GMDSS, has been developed by the maritime nations in the IMO and was adopted at an International Conference in 1988 [9] and implemented on the 1st of February 1992 which revolutionized the way distress, urgency and safety information was transmitted, coordinated, and managed on a worldwide basis. The fundamental concept of the GMDSS is the creation of conditions so that, in the event of an incident or accident at sea, the search and rescue authorities on shore as well as the maritime navigation in the vicinity of the ship or injured persons, can be quickly alerted so that subsequent search and rescue actions can be triggered in the shortest possible time, in a coordinated and effective manner.

The GMDSS therefore provides that every ship, while at sea, shall be able to perform the following nine basic communication functions[9]: Transmitting ship-to-shore distress alerts (by at least two separate and independent methods); Receiving shore-to-ship distress alerts; Transmitting and receiving ship-to-ship distress alerts; Transmitting and receiving search and rescue coordinating communications; Transmitting and receiving on-scene communications; Transmitting and

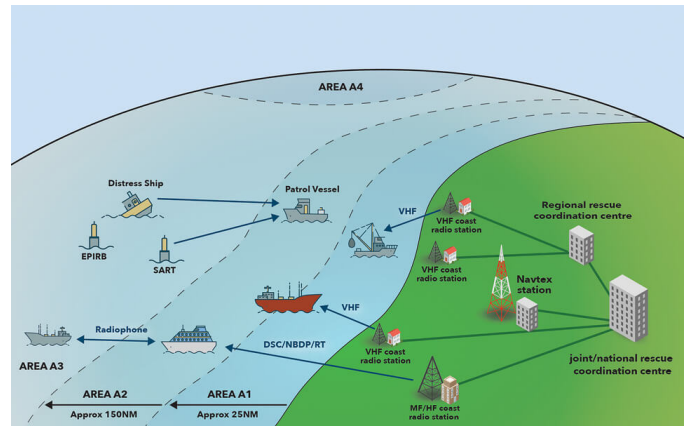


Fig. 1. GMDSS coverage areas: A1 - VHF coverage; A2 - MF coverage; A3 - geostationary satellite coverage; A4 - Area outside areas A1, A2 and A3 (Primary HF coverage) [11]

receiving signals for locating; Transmitting and receiving maritime safety information; Transmitting and receiving general communications; Transmitting and receiving bridge-to-bridge communications.

Radio services to be provided: A radiocommunication service utilizing geostationary satellites in the maritime mobile satellite service (International Maritime Satellite (INMARSAT)); A radiocommunication service utilizing polar orbiting satellites in the mobile satellite service (Space System for the Search of Vessels in Distress (COSPAS)-Search and Rescue Satellite - Aided Tracking (SARSAT)); A radiocommunication service for transmitting signals from survival craft stations in the 9200 MHz and 9500 MHz band (SART); Maritime mobile service in the bands between 156 MHz and 174 MHz (Very High Frequency (VHF)); Maritime mobile service in the bands between 4 000 kHz and 27 500 kHz (High Frequency (HF)); Maritime mobile service in the bands 415 kHz to 535 kHz and 1 605 kHz to 4 000 kHz (Medium Frequency (MF)).

In this sense, and considering that the different subsystems of the GMDSS have individual limitations in terms of geographical coverage and services provided, the equipment to be installed on ships is mainly determined by the area of operation of the ships themselves, so the GMDSS comprises four maritime areas, has illustrated in Figure 1 [10].

In 1979, a Conference convened by the IMO in Hamburg, adopted the SAR Convention [12]. This Convention was aimed at developing an international SAR plan, so that, no matter where an accident occurs, the rescue of persons in distress at sea will be coordinated by a SAR Organization and, when necessary, by cooperation between neighbouring SAR Organisations [13].

Following the adoption of the 1979 SAR Convention [12], IMO Maritime Safety Committee divided the world oceans into several search and rescue areas (Figure 2), in each of which the countries concerned have delimited search and rescue regions for which they are responsible.

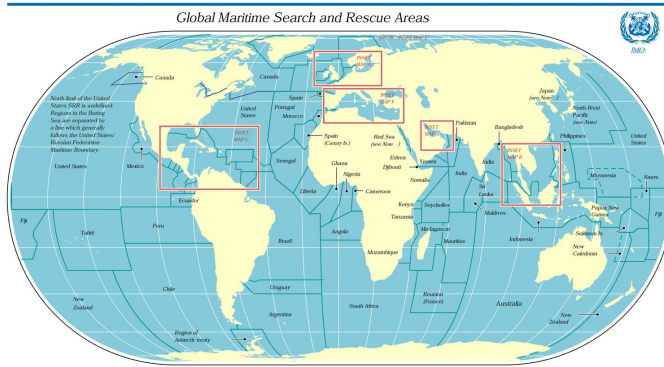


Fig. 2. World oceans divided into search and rescue areas defined by the IMO Maritime Safety Committee [12]

B. GMDSS Portugal

In 1985, the Portuguese Government approved, with a Decree-Law [14], the accession of the 1979 SAR Convention [12] and in order to ensure the objectives outlined by this Convention, the National SAR Organization was established by Decree-Law N° 15/94 of January 22nd [2] with the creation of the Sistema Nacional para a Busca e Salvamento Marítimo (SNBSM) [15] and with the Decree-Law N° 174/94 of June 25th the implementation of a national system applying the GMDSS rules [16].

The Search and Rescue Region (SRR) defined for Portugal derive from the 1979 SAR Convention [12] and the geographical limits, for the area of national responsibility (Figure 3), are found in Decree-Law N° 15/94 of January 22nd [2], amended by the Decree-Law N° 399/99 of October 14th [17].

The coordination of maritime search and rescue operations is carried out in the following control centres: Maritime Rescue Coordination Centre (MRCC) Lisboa - Comando Naval, Almada; MRCC Delgada - Comando da Zona Marítima dos Açores, Ponta Delgada; Maritime Rescue Coordination Subcentre (MRSC) Funchal - Comando da Zona Marítima da Madeira, Funchal.

The MRCC Lisbon, Delgada and the MRSC Funchal are connected with several radiocommunication coast stations and they maintain a 24/7 watchkeeping on international distress frequencies. The Technical Directorate responsible is Direção de Tecnologias da Informação e Comunicações (DITIC) that is located in Lisbon.

This paper focuses on VHF radio coverage in the Azores archipelago and from this point on, the work will aim more on this area regardless the fact that GMDSS is built in a national panorama and not only in this region.

C. State of the art

The 1974 SOLAS Convention [9] prescribes that all ships subject to that Convention are required to be fitted for GMDSS by the 1st of February 1999 and has urged administrations to implement GMDSS also for non-SOLAS vessels under national legislation as soon as possible and to encourage all maritime vessels voluntarily carrying maritime VHF radio



Fig. 3. Portugal SRR areas: SRR Santa Maria with 5 181 934 km²; SRR Lisboa with 572 914 km² [2], [17]

equipment to be fitted with VHF digital selective calling (DSC) no later than the 1st of February 2005.

The information concerning the implementation of the GMDSS shore-based facilities worldwide, including operational and planned sea areas A1 (VHF and VHF DSC) is disseminated by IMO in GMDSS/Circ. 8 [18] and GMDSS/Circ. 8/Corr. 5 [19], was issued on the 30th of April 2002 and contains information concerning almost 1400 VHF/DSC stations. With these numbers, IMO, decided that after the 1st of February 2005 continuous watchkeeping in VHF Channel 16 (156.800 MHz) is postponed. This was a step taken to mitigate the fatigue of the elements at the bridge, however, where practicable, it is advised to maintain watch on Channel 16 (156.800 MHz) when within the service area of a coast station providing international maritime mobile radio-telephone service in the band between 156 MHz and 174 MHz.

1) *Type of MMS stations:* Ship station - A ship station is a radio station established on board a ship for communications with stations ashore and other ship stations. Ship stations, where so equipped, shall, while at sea, maintain an automatic DSC watch on the appropriate distress and safety calling frequencies in the frequency bands in which they are operating; Coast station - A coast radio station is a radio station established on land for the purpose of communicating with ships at sea. Those coast stations assuming a watchkeeping responsibility in the GMDSS shall maintain an automatic digital selective calling watch on frequencies and for periods of time as indicated in the information published in the List of Coast Stations and Special Service Stations [8]; Port operations station - Port operations stations are established for the operational control of ships in and around ports and harbours; MRCC - Primary search and rescue facility in a

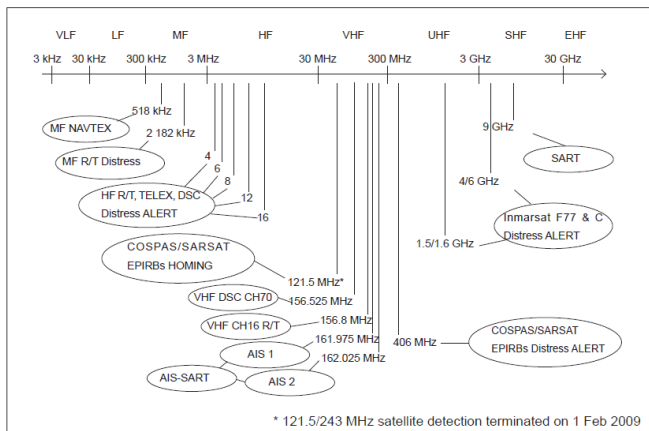


Fig. 4. Bands of frequencies throughout the radio frequency spectrum to the MMS regarding GMDSS allocate by the ITU[20]

country that is staffed by supervisory personnel and equipped for coordinating and controlling search and rescue operations. The MRCC facility is connected by various communications links to coast radio stations and other search and rescue Organisations (e.g. Air Rescue Coordination Centre (ARCC)).

All this stations shall be capable of offering four levels of priority in the following order: 1 - Distress calls, distress messages, and distress traffic; 2 - Urgency communications; 3 - Safety communications; 4 - Other communications.

2) *Frequencies allocated to the MMS*: The ITU has allocated various bands of frequencies throughout the radio frequency spectrum to the MMS regarding GMDSS [8] (see Figure 4) where there are some exclusive MMS channels important to this paper as Channel 16 (156.800 MHz): Radio telephony (RT) for Distress, Urgency, Safety and Calling and Channel 70 (156.525 MHz): Digital Selective Calling for Distress, Safety and calling - DSC.

3) *Maritime VHF Radio services - GMDSS*: Coast stations assuming a watchkeeping responsibility in the GMDSS shall maintain an automatic DSC (Channel 70) and a RT (Channel 16) watch with basic equipment required in each subsystem (example of a VHF subsystem in Figure 5a) to provide a response to an A1 distress alert. A country with an extended coastline may need a number of VHF base stations for effective radio coverage, in which one RCC supervises a number of geographically based subsystems like is shown in Figure 5b. Ship stations must be provided with a VHF radio installation capable of transmitting and receiving DSC on the frequency 156.525 MHz (Channel 70) and a RT equipment capable of working on the frequencies 156.300 MHz (Channel 6), 156.650 MHz (Channel 13) and 156.800 MHz (Channel 16). This radio must have an output power between 6 W and 25 W and the sensitivity of the receiver should be equal to or better than 2 μ V e.m.f. for a signal-to-noise ratio of 20 dB.

III. AZORES VHF MMS SYSTEM ARCHITECTURE

Reminding that the fundamentals of GMDSS is to make sure that the search and rescue authorities ashore, will be rapidly alerted to a distress incident so they can assist in a

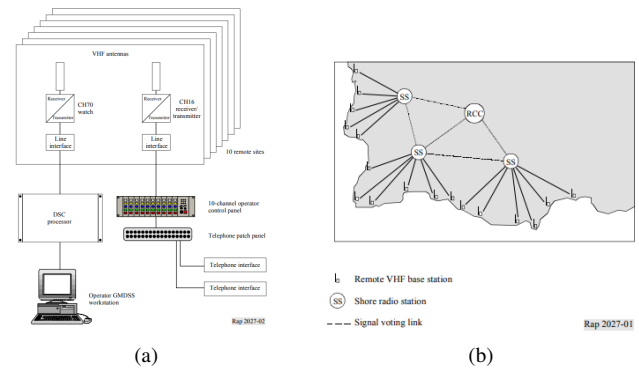


Fig. 5. (a) represents a basic GMDSS A1 subsystem [21]. (b) represents a typical system covering coastline that needs a number of VHF base stations for effective radio coverage [21].

Local designation	Coordinates	Altitude
Morro Alto (Flores)	N39°27'48.52",W031°13'13.38"	918 m
Cabeço Gordo (Faial)	N38°34'33.00",W028°42'46.00"	1040 m
Santa Bárbara (Terceira)	N38°43'47.72",W027°19'08.70"	1020 m
Sete Cidades (São Miguel)	N37°50'26.00",W025°47'53.00"	560 m
CZMA (São Miguel)	N37°44'15.40",W025°40'15.90"	28 m
Pico da Barrosa (São Miguel)	N37°45'34.87",W025°29'30.64"	930 m
Pico Bartolomeu (São Miguel)	N37°46'42.00",W025°10'35.00"	860 m
Pico Alto (Santa Maria)	N36°58'58.00",W025°05'26.00"	561 m

TABLE I
AZORES VHF MMS COAST STATIONS LOCATIONS

coordinate SAR operation with the minimum delay, one should ensure the proper infrastructures for the radio coverage in the defined areas. Hence, the selection of VHF coast stations for sea area A1 should: Be affiliated to an RCC and have reliable communications by telephone and telex; Have short-range VHF capability; Provide as complete a coverage of their immediate sea area as possible; Be in continuous operation.

A. Locations

The Portuguese Navy VHF communications coast stations are located in the geographic positions described in Table I which are operated remotely by the MRCC Delgada but also can be accessed by the MRCC Lisbon. Remote access is achieved through the Rede Comunicações da Marinha (RCM) which is the Portuguese Navy private Internet Protocol (IP) network.

B. Architecture of the system

All MRCC have implemented two separate consoles for system operation VHF voice and DSC: Dispatch console (RT circuits) and DSC console (treatment of DSC messages).

The dispatch console gathers the operation functions of the circuits of voice and control of their communications equipment. This console has access to a call recording system, for archiving as well as for immediate response, in case of simultaneous calls at different radio stations. It contains interconnection with the fixed and mobile telephony system of the RCM, by interfacing with its component analogue and/or Voice over Internet Protocol (VoIP), providing the radio channel interconnection capacity with a fixed network

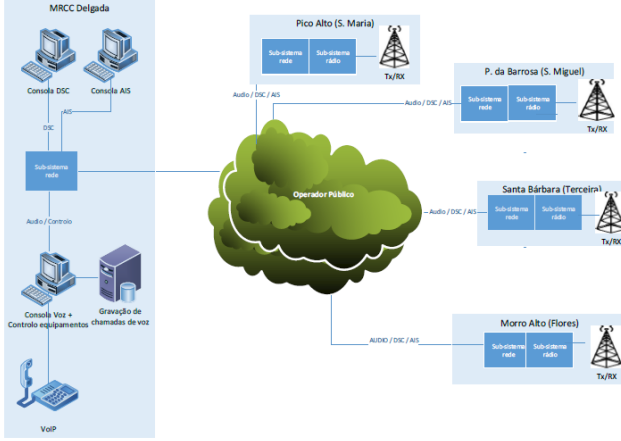


Fig. 6. Azores VHF MMS system architecture representation

or mobile network user (see Figure 6). The DSC console performs all operations related to message handling of this system. The DSC system is based on a web server architecture and access to console is made by web browser. Regarding transport technologies, the whole system (voice, DSC and Automatic Identification System (AIS)) is made on full-IP.

C. Guidance criteria according with IMO Resolution A.801(19)

According to [10], sea area A1 is that sea area which is within a circle of radius A NM over which the radio propagation path lies substantially over water. The radius A is equal to the transmission distance between a ship VHF antenna at a height of ≈ 4 m above sea level and the antenna of the VHF coast station which lies at the centre of the circle.

The following equation should be used to calculate the range (A) of the transmitter in NM (distance from antenna to the visible horizon):

$$A_{[NM]} = 2.5 \left(\sqrt{H_{[m]}} + \sqrt{h_{[m]}} \right) \quad (1)$$

where H is the height of the coast station VHF receiving antenna and h is the height of the ship transmitting antenna.

D. Range of Azores VHF coast stations, IMO Resolution A.801(19)

Using Equation 1 and assuming that $h = 4$ m one finding the results in Table 2. Figure 7 illustrates the coverage of the coastal stations located in Azores archipelago described in Table I.

IV. PROPAGATION MODEL: ITU-R P.1546-6 RECOMMENDATION

The analytical methods developed by the ITU, which are in its resolutions and publications, focus mainly on determining the value of the electromagnetic field strength as a function of the distance between the transmitting and receiving antennas. Nevertheless, radio operators who must decide how to use

Local designation	Radio range _[NM]
Morro Alto (Flores)	80.74
Cabeço Gordo (Faial)	85.21
Santa Bárbara (Terceira)	84.84
Sete Cidades (São Miguel)	64.16
CZMA (São Miguel)	18.22
Pico da Barrosa (São Miguel)	81.23
Pico Bartolomeu (São Miguel)	78.31
Pico Alto (Santa Maria)	64.21

TABLE II
AZORES VHF MMS COAST STATIONS RADIO RANGE

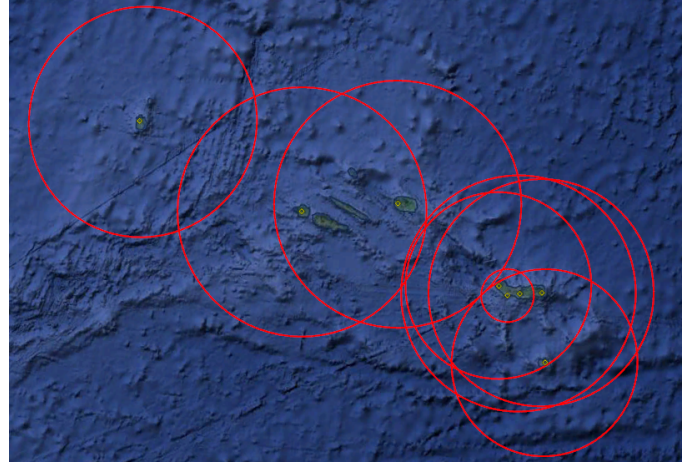


Fig. 7. Radius of the coverage for each coast station following the guidance criteria of IMO Resolution A.801(19)

the means of communications effectively, are interested not in the field strength, but rather if it is possible to carry out correspondence over a certain distance [22]. Hence, the developed equation in [10] (Equation 1) is widely used in the literature and textbooks for radio operators.

However, the transmission of a radio signal through a wireless radio channel is affected by refraction, diffraction, reflection, object penetration, absorption, among others, that corrupt the originally transmitted signal before the radio wave arrives at a receiver antenna. Thus, it will be essential to choose and develop a new coverage analysis based on a more complete radio wave propagation model in order to foresee all the above-mentioned constraints.

The main scope of the ITU-R P.1546-6 Recommendation [23] is to describe a method for point-to-area radio propagation predictions for terrestrial services in the frequency range 30 MHz to 4 000 MHz. It is intended for use on tropospheric radio circuits over land paths, sea paths and/or mixed land-sea paths up to 1 000 km length for effective transmitting antenna heights less than 3 km. The method is based on interpolation/extrapolation from empirically derived field strength curves as function of distance, antenna height, frequency and percentage time. The computation process also includes corrections to the results obtained from this interpolation/extrapolation to account for terrain clearance and terminal clutter obstructions [23]. The ITU-R P.1546-6 Recommendation provides a set of curves and tables of field strength as a function of frequency (100 MHz, 600 MHz, and 2

000 MHz), distance (1 to 1000 km), transmitting/base antenna height (10 m to 1000 m), percentage of time exceeded (50%, 10%, and 1%), and path type (land, cold sea, and warm sea). In order to apply this Recommendation to all conditions besides the ones registered on the tabulated values, one should proceed to some corrections. The next Subsections describes the most relevant corrections to this study.

A. Transmitting/base antenna height

The Recommendation takes account of the effective height of the transmitting/base antenna, which is the height of the antenna above terrain height averaged between distances of 3 to 15 km in the direction of the receiving/mobile antenna. The transmitting/ base antenna height (h_1), to be used in the computations, depends on the type and length of the path and on the availability of terrain information.

In this study, one has access to terrain information. Hence, the transmitting/base antenna height is given by:

$$h_{1[m]} = \begin{cases} h_b, & d < 15\text{km} \\ h_{eff}, & d \geq 15\text{km} \end{cases} \quad (2)$$

From the transmitting/base antenna in the direction of the receiving/mobile antenna, h_b is the height of the antenna above terrain height averaged between 0.2d and d km. h_{eff} is the height of the antenna above terrain height averaged between 3 km and 15 km.

B. Mixed path

In case the path between the transmitting/base antenna and the receiving/mobile antenna is composed of at least a portion of land and a portion of sea, this path should be treated as mixed path (Figure 8).

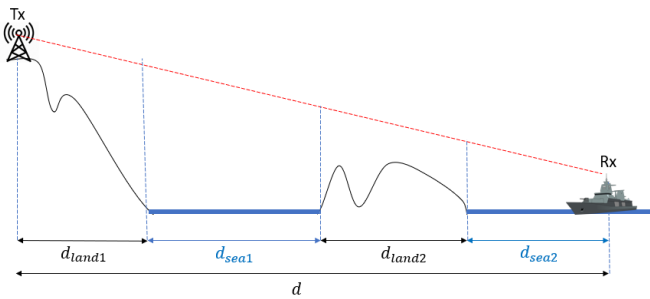


Fig. 8. In order to determine the field strength on a mixed path the value of h_1 should be calculated like in a single type of path and used for both $E_{land}(d)$ and $E_{sea}(d)$

The mixed path field strength, E , is evaluated as :

$$E = (1 - A) \cdot E_{land}(d_{total}) + E_{sea}(d_{total}) \quad (3)$$

where A is the mixed path interpolation factor found from:

$$A = A_0(F_{sea})^V \quad (4)$$

F_{sea} is the fraction of the total path between the transmitting/base antenna and the receiving/mobile antenna over sea given by:

$$F_{sea} = \frac{d_{sT}}{d} \quad , \quad d_{sT}: \text{Total sea path distance(s)} \quad (5)$$

and $A_0(F_{sea})$ is the basic interpolation factor expressed as:

$$A_0(F_{sea}) = 1 - (1 - F_{sea})^{\frac{2}{3}} \quad (6)$$

In order to calculate V one should use:

$$V = \max \left[1.0, 1.0 + \frac{\Delta}{40.0} \right] \quad (7)$$

Where Δ is given by:

$$\Delta = E_{sea}(d) - E_{land}(d) \quad (8)$$

C. Terrain clearance angle

For land paths, the terrain clearance angle (TCA) correction may be added to increase the prediction accuracy, enabling obstacles that are close to the receiver/ mobile antenna. When a calculation for a mixed path is necessary, this correction should be included only if the receiving/mobile antenna is adjacent to a land section of the path. TCA can be shown to be equal to:

$$\theta_{tca[degrees]} = \theta \quad , \quad 0.55^\circ < \theta_{tca} < 40.0^\circ \quad (9)$$

where θ is the relative angle of the receiver line that tangents the obstructions at distances greater than 16 km in the direction of the transmitting/base station antenna and does not extend beyond it (Example: Figure 9).

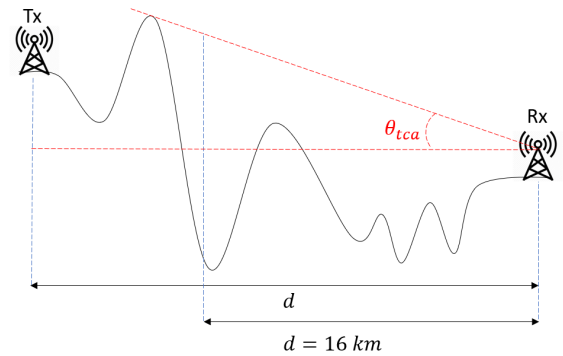


Fig. 9. All obstructions which are at a distance of less than 16 km will be ignored. Furthermore, to obtain θ the curvature of the Earth must not be taken into account.

The correction (C_{tca}) is found from:

$$C_{tca[dB]} = J(\nu') - J(\nu) \quad (10)$$

Where $J(\nu)$ is given by:

$$J_\nu = \begin{cases} 6.9 + 20 \log(\sqrt{(\nu - 0.1)^2 + 1} + \nu - 0.1), & \nu > -0.7806 \\ 0, & \text{otherwise} \end{cases} \quad (11)$$

and:

$$\nu' = 0.036 \sqrt{f_{[MHz]}} \quad (12)$$

$$\nu = 0.065 \theta_{tca[degrees]} \sqrt{f_{[MHz]}} \quad (13)$$

D. Correction for receiving/ mobile antenna height

In this Recommendation, besides the height of the receiving/mobile antenna (h_2), the coverage of the ground around it (R_2) can also be taken into account, and in case of need, perform a correction. Depending on the environment, the average height of obstacles that can surround a mobile receiver/antenna are:

- Dense urban area: $R_2 = 20$ m;
- Urban area: $R_2 = 15$ m;
- Suburban area: $R_2 = 10$ m;
- Sea paths: $R_2 = 10$ m.

If the receiving/ mobile antenna is located over the sea or adjacent to sea and $h_2 < 10$ m, one should use a method to calculate the correction based upon the path lengths at which 60% of the first Fresnel zone is just clear of obstruction by the sea surface. The correction for receiving/ mobile antenna height (C) is given by:

$$C_{[dB]} = \begin{cases} 0.0, & \text{for } d \leq d_{h2} \\ C_{10} \left(\frac{\log\left(\frac{d}{d_{h2}}\right)}{\log\left(\frac{d_{10}}{d_{h2}}\right)} \right), & \text{for } d_{h2} < d < d_{10} \end{cases} \quad (14)$$

where:

$$C_{10} = K_{h2} \log\left(\frac{h_2}{10}\right) \quad (15)$$

$$d_{10[km]} = D_{06}(f, h_1, 10) \quad (16)$$

$$d_{h2[km]} = D_{06}(f, h_1, h_2) \quad (17)$$

The path length at which 60% of the first Fresnel zone is just clear of obstruction if given by:

$$D_{06[km]} = \frac{D_f D_h}{D_f + D_h} \quad (18)$$

and:

$$D_f[km] = 0.000389 \cdot f_{[MHz]} \cdot h_{1[m]} h_{2[m]} \quad (19)$$

$$D_h[km] = 4.1 \left(\sqrt{h_{1[m]}} + \sqrt{h_{2[m]}} \right) \quad (20)$$

E. Location variability

The propagation curves in [23] represent the field strength values exceeded at 50% of locations within an area of approximately 500 m by 500 m. In case that is necessary to proceed to other values than $l = 50\%$ one should consider a correction given by:

$$E(l)_{[dB(\mu V/m)]} = E(\text{median}) + Q_i \left(\frac{p}{100} \right) \sigma_L \quad (21)$$

Considering that this Recommendation does not consider any value for σ_L for a sea environment, one should consider that $Q_i \left(\frac{p}{100} \right) \sigma_L = -10$ dB.

V. MODEL IMPLEMENTATION AND ANALYSES

A. Model implementation

The model chosen to implement in the calculation of the VHF coverage of the Portuguese Navy GMDSS coastal stations in the Azores archipelago will be the ITU-R P.1546-6 Recommendation[23]. Subsequently, the results will be compared with actual measurements taken on the Azores archipelago and the Okumura-Hata model[24] in order to assess the model error.

All calculations were performed by computational means, namely using the PyCharm® program (Python language) and the code was adapted from [25] and [26]. The fixed parameters used on the simulator are: frequency ($f = 156.800$ MHz); time variability ($t = 50\%$) and location variability ($l = 50\%$). All the others parameters depend on the location of the receiving/ mobile antenna and the transmitter/ base antenna chosen.

The data for the calculation of h_1 will be obtained by accessing to Open-Elevation API [27]. The script takes about 1000 elevation points along the path between the transmitter and the receiver.

After all the calculations based on the tabulated values of [23] one should get a value of field strength that depending on the environment between both antennas needs to proceed to eventual corrections like described in IV.

In case that it is necessary to calculate an equivalent power transmission (P_{eq}) different than the one used on [23], one should consider that:

$$E_{eq[dB(\mu V/m)]} = E_{[dB(\mu V/m)]} + 10 \log(P_{eq[kW]}) \quad (22)$$

B. Results

Taking advantage of the measurements taken on the islands by a civil company that was contracted to modernize three coastal stations (Pico da Barrosa - São Miguel Island, Morro Alto - Flores Island and Pico Alto - Santa Maria Island), the values obtained will be compared with those calculated using ITU-R P.1546-6 [23] Recommendation and Okumura-Hata model [24].

In order to quantify the prediction quality of a radio propagation model, three statistical parameters are usually used:

The mean absolute error (MAE) that represents the differential between the actual measured power value (P_m) versus the estimated theoretical power value (P_p) and is evaluated as:

$$MAE_{[dB]} = \frac{1}{N} \sum_{i=1}^N |P_{m(i)} - P_{p(i)}| \quad (23)$$

The root mean square error (RMSE) that is the square root of the quadratic mean between the predicted value and the observed value is given by:

$$RMSE_{[dB]} = \sqrt{\frac{1}{N} \sum_{i=1}^N (|P_{m(i)} - P_{p(i)}|)^2} \quad (24)$$

The standard deviation (σ) represents the measure of the amount of variation between the estimated value and the real

measured value and is defined as:

$$\sigma_{[\text{dB}]} = \sqrt{\frac{1}{N} \sum_{i=1}^N (|P_{m(i)} - P_{p(i)}| - MAE)^2} \quad (25)$$

Comparing the data obtained between the values measured on-site with the theoretical results using [23] and [24], the resulting statistical error values are as follows (Table III):

Local	Model	MAE _[dB]	RMSE _[dB]	σ _[dB]
Pico Barrosa	ITU-R P.1546-6	16.272	18.107	7.940
	Okumura-Hata	13.627	15.653	7.699
Morro Alto	ITU-R P.1546-6	17.762	20.377	9.987
	Okumura-Hata	17.039	19.374	9.221
Pico Alto	ITU-R P.1546-6	7.723	9.479	5.497
	Okumura-Hata	8.547	9.644	4.468

TABLE III
ERROR STATISTICS

By analysing the results, the values obtained are not encouraging due to the high values of MAE, RMSE and σ . Thus, one should proceed to a correction on the ITU-R P.1546-6 Recommendation [23].

C. ITU-R 1546-6 Recommendation correction

Considering only the correction TCA that is described in Section IV, which contemplates only the largest obstacle between the receiving antenna and the transmitting antenna at a distance up to 16 km, one should adapt the Recommendation in order to get an accurate result in the Azores archipelago that is clearly an irregular terrain with a lot of isolated obstacles. According with [28], a general method can be used for an irregular terrain environment assuming that the terrain profile between the transmitting antenna and the receiving antenna is represented by a set of n points, each of which is defined by the horizontal distance from the transmitter d_i and the elevation h_i .

The main obstacle (op) between the sending and receiving antennas is identified as in Deygout method [29] and the attenuation caused by the obstacle is given by[30]:

$$A_{obs[\text{dB}]} = 10 \log_{10} \left(\frac{[\frac{1}{2} + Ci(-v)]^2}{2} + \frac{[\frac{1}{2} + Si(-v)]^2}{2} \right) \quad (26)$$

Ci and Si represents the Fresnel integrals and the variable ν is given by:

$$\nu = -\sqrt{\frac{2d}{\lambda d_1 d_2}} \bar{x} \quad (27)$$

Where \bar{x} is the distance from the direct ray between antennas [30] and the top of the obstacle (see Figure 10). This value can have positive or negative values and is calculated as follows [30]:

$$\bar{x} = \frac{(h_t - h_{op}) d_2 + (h_r - h_{op}) d_1}{d} \quad (28)$$

If there is more than one obstacle between antennas, one should apply the Deygout method [29] twice more - one

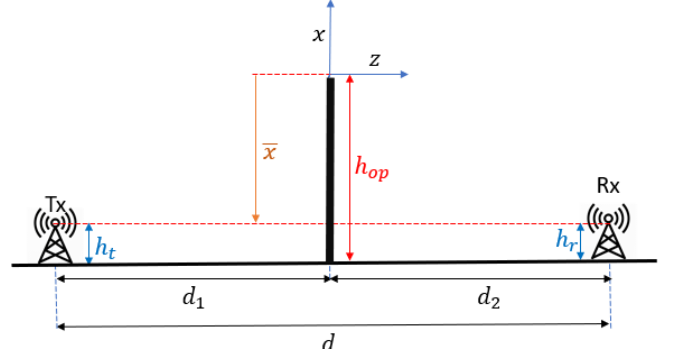


Fig. 10. Distance from the direct ray between antennas and the top of the obstacle (\bar{x})

between the transmitting antenna and the main obstacle (ot) and another one between the main obstacle and the receiving antenna (or). If $\nu > -0.7$, $A_{obs}(\nu_x)$ can be approximated using Equation 11. The diffraction attenuation on the path between the transmitting antenna and the receiving antenna is the attenuation due to the main obstacle plus the sum of the attenuation of the obstacles on either side of the main obstacle and a corrective term, all multiplied by a factor that depends on the attenuation of the main obstacle, considered as an knife-edge. This correction is given by:

$$A_{obs(total)[\text{dB}]} = A_{obs}(v_{op}) + T [A_{obs}(v_{ot}) + A_{obs}(v_{or}) + C] \quad (29)$$

where:

$$C = 10 + 0.04 d_{[\text{km}]} \quad (30)$$

$$T = 1.0 - \exp \left[-\frac{A_{obs}(v_{op})}{6.0} \right] \quad (31)$$

D. Results with ITU-R P.1546-6 correction

With the same parameters used previously, but this time applying the method described in [28] instead of the TCA correction, the values obtained are as represented in Table IV.

Local	Model	MAE _[dB]	RMSE _[dB]	σ _[dB]
Pico Barrosa	ITU-R P.1546-6	16.272	18.107	7.940
	Okumura-Hata	13.627	15.653	7.699
	ITU-R P.1546-6 + C	4.618	5.474	2.938
Morro Alto	ITU-R P.1546-6	17.762	20.377	9.987
	Okumura-Hata	17.039	19.374	9.221
	ITU-R P.1546-6 + C	6.131	7.433	4.202
Pico Alto	ITU-R P.1546-6	7.723	9.479	5.497
	Okumura-Hata	8.547	9.644	4.468
	ITU-R P.1546-6 + C	3.776	4.273	2.000

TABLE IV
ERROR STATISTICS WITH CORRECTION OF ITU-R P.1546-6
RECOMMENDATION

Comparing the results obtained with the correction it can be seen that the values obtained are very close to the one measure on location. Hence, it can be concluded that ITU-R P.1546-6 with the correction is a good model for the computation of the VHF MMS GMDSS system coverage in the Azores archipelago.

E. Coverage of the VHF Portuguese Navy GMDSS coastal stations in the Azores archipelago

In order to verify the VHF coverage of the GMDSS system in the Azores archipelago, the transmitter antenna height chosen for the coastal stations are in accordance with the equipment referred in Table I, the transmission power for all transmitters is 25 W and the frequency is 156.800 MHz. In the case of the receivers (one should assume that all are ships), a sensitivity of $0.3 \mu\text{V}$ was set taking as a reference to the equipment used in the Portuguese Navy and the antenna height will be 4 m. The time variability is 50%, the type of path is mixed and considering that the receiver is in a sea environment that can be very unstable and hard to predict (state of the sea dependent) one should consider a loss of 10 dB due to location variability and factor K is $4/3$.

The resulting coverage from the computations for each coastal station are represented in Figure 11.

F. Analyses

When analysing Figure 11, it is noticeable the difference between the results obtained with the calculation following IMO Resolution A.801(19) [10]. The total radio coverage area is approximate $68\,332 \text{ NM}^2$ and almost 40% of this area is guaranteed by more than one coastal station, which is good because it ensures that, in the event of a total failure of a coastal station, the coverage area guaranteed by it can be assured by another adjacent coastal station. Table V indicates the number of overlapping VHF radio coverage per area[%]. Nevertheless, there are two radio shadow areas identified, one in the south of Pico Island (Figure 12a) and another, which can be ignored due to low maritime traffic (Figure 12b), located in the north of Corvo Island.

N° of overlapping VHF radio coverage per area	0	1	2	3	4	5
Area size [%]	0.09	60.92	23.49	10.71	3.53	1.27

TABLE V
N° OF OVERLAPPING VHF RADIO COVERAGE PER AREA[%]

G. Proposed solution

Based on a site survey carried out by the Portuguese Navy in 2013 throughout the Azores archipelago, a site already exploited by Portugal Telecom was identified, which is located in Cabeço Geraldo on Pico Island (N $38^\circ 24' 4.70''$, W $28^\circ 14' 3.90''$). When computing the data for this location, it is verified with Figure 12d the area without radio coverage identified in the south of Pico Island disappears completely being in this way an excellent option for the reinforcement of the radio coverage for area A1 of the GMDSS system. Analysing all the areas covered by only one coastal station (see Figure 12c), the radio coverage that overlaps the central group of the Azores archipelago should be improved since it is an area with a high density of maritime traffic especially in the São Jorge Canal and in the southwest of the island of Pico. Hence, of the locations identified in the above-mentioned site

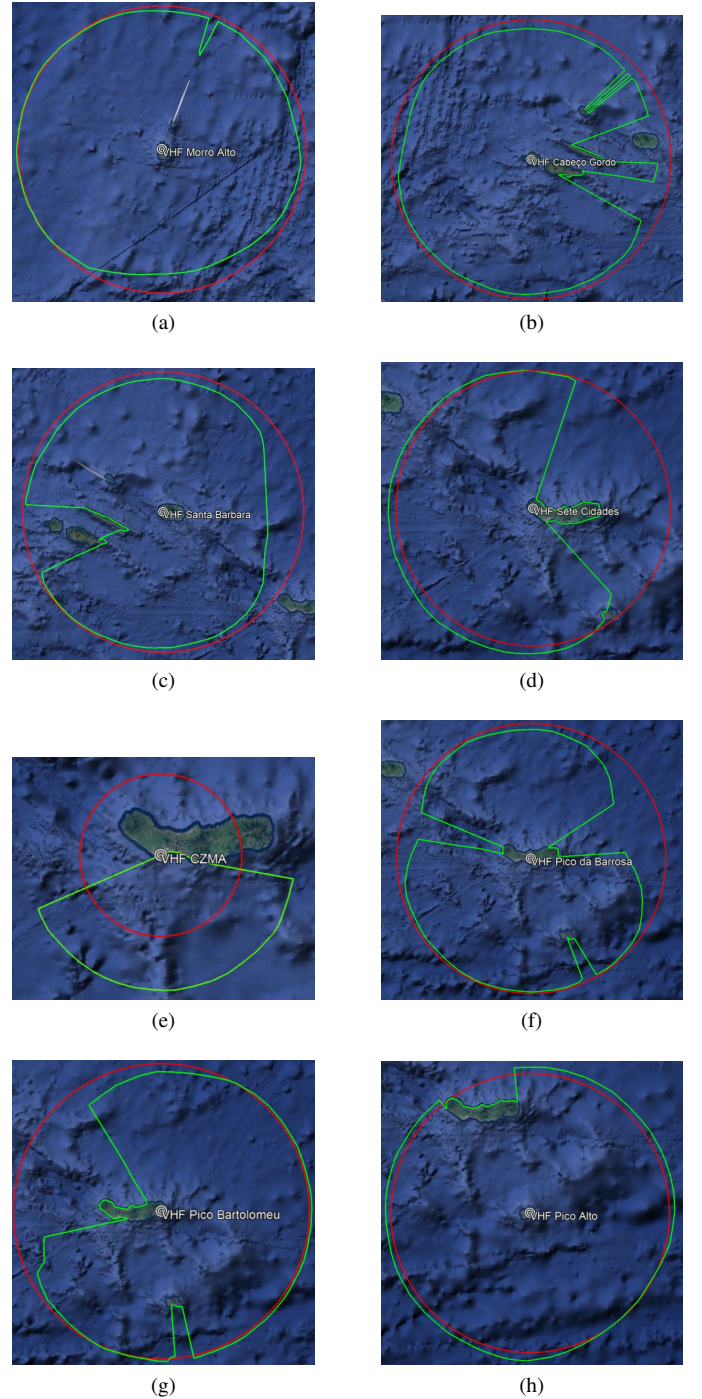


Fig. 11. VHF MMS coverage from the Portuguese Navy coast stations: (a) Morro Alto; (b) Cabeço Gordo; (c) Santa Bárbara; (d) Sete Cidades; (e) CZMA; (f) Pico Barrosa; (g) Pico Bartolomeu; (h) Pico Alto

survey, the installation of a coastal station at Macela, São Jorge Island, that is a building owned by Proteção Civil, despite not being perfect due to the orography of the island, is the best located to cover the São Jorge Canal. The results are shown in Figure 12d and in Table VI.

VI. CONCLUSION

In order to obtain the Portuguese Navy coast stations VHF MMS coverage of the GMDSS system, it was applied, by

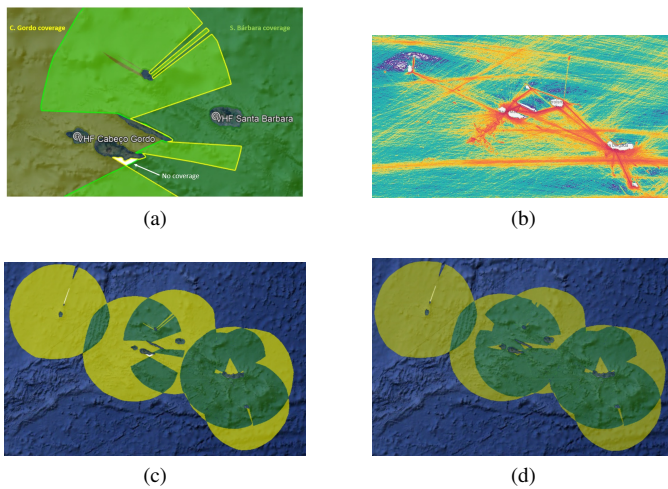


Fig. 12. (a) Radio shadow area in the south of Pico island; (b) Maritime traffic density map - Azores archipelago; (c) Portuguese Navy VHF MMS coverage - yellow identifies coverage by only one coast station and white polygons identifies shadow areas; (d) Portuguese Navy VHF MMS coverage with proposed solution - yellow identifies coverage by only one coast station

N° of overlapping VHF radio coverage per area	0	1	2	3	4	5
Area size[%]	0.05	50.26	20.06	20.46	3.90	1.27
Difference[%]	-49	-17	3	92	11	0

TABLE VI
N° OF OVERLAPPING VHF RADIO COVERAGE PER AREA [%] WITH PROPOSED SOLUTION

computational means, the ITU-R P.1546-6 Recommendation with a correction. With the results obtained for each coastal station, it was concluded that there are many signal losses by diffraction and two areas without radio coverage were even identified - one at the north of Corvo Island and another at the south of Pico Island. Finally, it was suggested, based on the density of the maritime traffic at the Azores archipelago, a solution to eliminate the area without radio coverage identified in the south of Pico Island with the installation of a VHF coastal station in Cabeço de Geraldo. In order to ensure better resilience in the São Jorge Canal, was also suggested the installation of a coastal station in Macela, on São Jorge Island.

ACKNOWLEDGMENT

I, Frederico Neto, would like to express my gratitude to the Instituto de Telecomunicações and to my supervisors, Prof. António Fernandes and José Sanguino, for having guided, motivated, shared of knowledge and supported me, with quality.

REFERENCES

- [1] E. Bolas, "Broadband VHF maritime communications based on cognitive radio," Ph.D. dissertation, Universidade de Aveiro, 2016.
- [2] Ministério da Defesa Nacional, "Decreto-Lei n.º 15/94 de 22 de Janeiro - Cria o Sistema Nacional para a Busca e Salvamento Marítimo, Diário da República n.º 18/1994, Série I-A," Lisboa, Portugal.
- [3] Neal McEwen. (1999) 'SOS,' 'CQD' and the History of Maritime Distress Calls. Accessed November-2020. [Online]. Available: <http://www.telegraph-office.com/pages/arc2-2.html>
- [4] T. Telegraph. (2017, March) "The first ever radio distress call is made off Kent coast". Accessed November-2021. [Online]. Available: <https://www.telegraph.co.uk/technology/connecting-britain/first-ever-radio-distress-call/>

- [5] Nobel Media AB2020. (2020) Guglielmo Marconi – Biographical. Accessed November-2020. [Online]. Available: <https://www.nobelprize.org/prizes/physics/1909/marconi/biographical/>
- [6] UK Science Museum. (2018) Titanic, Marconi and the wireless telegraph. Accessed November-2020. [Online]. Available: <https://www.sciencemuseum.org.uk/objects-and-stories/titanic-marconi-and-wireless-telegraph>
- [7] C. Hempstead, "SUNGOOK HONG, Wireless: From Marconi's Black-box to the Audion. Transformations: Studies in the history of Science and Technology. Cambridge, MA and London: MIT Press, 2001." 2003.
- [8] IMO. SOLAS Convention 1974. Accessed November-2020. [Online]. Available: [https://www.imo.org/en/About/Conventions/Pages/International-Convention-for-the-Safety-of-Life-at-Sea-\(SOLAS\)-1974.aspx](https://www.imo.org/en/About/Conventions/Pages/International-Convention-for-the-Safety-of-Life-at-Sea-(SOLAS)-1974.aspx)
- [9] IMO, "Protocol of 1988 International Convention for the Safety at Sea, 1988."
- [10] IMO, "Provision of radio services for the Global Maritime Distress and Safety System (GMDSS), Resolution A.801(19)," 1995.
- [11] K. of the sea. GMDSS coverage areas. Accessed December-2020. [Online]. Available: <https://knowledgeofsea.com/gmdss-equipments-and-procedures/>
- [12] IMO, "International Convention on Maritime Search and Rescue (SAR)," 1979.
- [13] IMO. SAR Convention 1979. Accessed December-2020. [Online]. Available: <https://www.imo.org/en/OurWork/Safety/Pages/SARConvention.aspx>
- [14] Ministério dos Negócios Estrangeiros - Direção-Geral dos Negócios Económicos, "Decreto-Lei n.º 32/85 de 16 de Agosto - Convenção Internacional sobre Busca e Salvamento Marítimo de 1979, Diário da República n.º 187/1985, Série I," Lisboa, Portugal.
- [15] C. Afonso, "Contributos para o plano integrado de Busca e Salvamento Marítimo Nacional," Research work, Instituto Universitário Militar, 2008.
- [16] Ministério das Obras Públicas, Transportes e Comunicações, "Decreto-Lei n.º 174/94 de 25 de Junho - Estabelece um sistema nacional de comunicações de socorro e segurança marítima que aplique as regras do GMDSS, Diário da República n.º 145/1994, Série I-A," Lisboa, Portugal.
- [17] Ministério da Defesa Nacional, "Decreto-Lei n.º 399/99 de 14 de Outubro - Altera o Decreto-Lei n.º 15/94 de 22 de Janeiro e o Decreto-Lei n.º 253/95 de 30 de Setembro, Diário da República n.º 240/1999, Série I-A," Lisboa, Portugal.
- [18] IMO, "Master plan of Shore-Based facilities for the Global Maritime Distress and Safety System (GMDSS MASTER PLAN), GMDSS/Circ.8," 1999.
- [19] —, "Master plan of Shore-Based facilities for the Global Maritime Distress and Safety System (GMDSS MASTER PLAN), GMDSS/Circ.8/Corr.5," 2002.
- [20] WCR-ITU, "World Radiocommunication Conference - Final Acts, 2007 Geneva, Swiss."
- [21] ITU, "Engineer Guidance for operators to upgrade shore facilities to operate the Global Maritime Distress and Safety System in the A1, A2 and A3/A4 sea areas, ITU-R M.2027 Report," 2001.
- [22] M. Maka and P. Majzner, "Propagation models for the Radiocommunication Event Management System (REMS) in the V-band," *Scientific Journals Maritime University of Szczecin, Zeszyty Naukowe Akademii Morskiej w Szczecinie*, vol. 58, pp. 55–60, 2019.
- [23] ITU, "Method for point-to-area predictions for terrestrial services in the frequency range 30 MHz to 4 000 MHz, ITU-R P.1546-6 Recommendation," 2019.
- [24] M. Hata, "Empirical formula for propagation loss in land mobile radio services," *IEEE Transactions on Vehicular Technology*, vol. 29, no. 3, pp. 317–325, 1980.
- [25] Mejías Cruz, Carlos, "Simulador en Python de métodos de predicción de punto a zona para servicios terrenales en la gama de frecuencias de 30 a 3 000 MHz," MSc. D., Universidad de Sevilla, 2019.
- [26] I. Stevanovic, "MATLAB/Octave implementation of ITU-R P.1546-6 Recommendation - Method for point-to-area predictions for terrestrial services in the frequency range 30 MHz to 4 000 MHz," 03 2021.
- [27] João Ricardo Lourenço. Open-elevation. Accessed May-2021. [Online]. Available: <https://open-elevation.com/>
- [28] C. Salema, "Feixes Hertzianos - Propagação por difração - Terreno Irregular". Instituto Superior Técnico press, 2002, p. 118.
- [29] J. Deygout, "Multiple knife-edge diffraction of microwaves," *IEEE Transactions on Antennas and Propagation*, vol. 14, no. 4, pp. 480–489, 1966.
- [30] C. A. Fernandes, "Radiopropagação," Lecture slides, Instituto Superior Técnico, 2020.