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Propagation models for the Radiocommunication Event Management System (REMS) in the V-band

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Abstract

This paper presents an analytical method for determining marine VHF communication bands based on the propagation model included in the International Telecommunication Union (ITU) recommendations. The developed method to determine communication bands was compared with the model recommended by the International Maritime Organization (IMO). The usefulness of the method developed by the authors has been demonstrated for the needs of the Radiocommunication Events Management System (REMS).

Introduction

Ship-to-ship or ship-to-shore short-range communication uses radiotelephones operating in the marine VHF band of 156–174 MHz. These radiotelephones are also the basic means of communication used by ships in distress in the sea area A1, as well as during correspondence at the scene of an accident in other shipping areas. The sea area A1 is an area where a ship is within radiotelephone coverage of at least one VHF coast station where continuous digital selective calling (DSC) (Ch.70/156.525 MHz), alerting, and radiotelephony services are available. The VHF marine band falls within the V band (30–300 MHz), where radio waves propagate straight as spatial waves and are reflected from high-density objects. They are also dispersed and attenuated in the atmosphere and other media mainly due to the presence of water (rainfall, fog, etc.). The theoretical range of ultrashort waves is limited to the optical horizon (Czajkowski, 2002), but in practice, this range is greater due to tropospheric refraction and diffraction.

Analytical methods developed in the second half of the 20th century, included in the ITU resolutions and publications, mainly focused on determining the value of electromagnetic field intensity as a function of the distance between transmitting and receiving antennas. The need to use complex formulas and interpolation of the characteristics of many parameters made it difficult for radiocommunication device users to quickly and practically apply these methods. Radio operators, who must decide how to use the means of communication, are interested not in the field strength, but rather if it is possible to carry out correspondence over a certain distance. Thus, the developed empirical relationships to determine the range of communication d expressed in nautical miles are widely used in the literature and textbooks for radio operators (IMO, 1995):

$$d = 2.5\left(\sqrt{h_1} + \sqrt{h_2}\right) \tag{1}$$

or expressed in kilometers (2):

$$d = 4.6\left(\sqrt{h_1} + \sqrt{h_2}\right) \tag{2}$$

where:
h_1 – height of the transmitting antenna [m],
h_2 – height of the receiving antenna [m].

However, the above formulae do not consider the type of modulation or the type of signal (radio-telephony or digital transmission – DSC).

In the case of communication with a shore station whose antennas are many meters above the surface, only one-way communication is sometimes possible, e.g., a ship radio station receives a signal from the shore station, but the signal transmitted from the ship is not received. In addition, this method does not take into account many of the factors affecting the communication range, such as changes in the conductivity of the ground along the path of the electromagnetic wave or the difference in the transmitter output power occurring in ship-to-shore communication.

In addition, the inability to use Eq. 2 to indicate differences in radiotelephony and DSC ranges causes problems in modeling decision-making processes in the Radiocommunication Events Management System (REMS). Thus, in this paper it was deemed necessary to analyze and adapt currently-used methods to the requirements of the REMS system being developed, especially due to changes in the provisions of the Radio Regulations and the introduction of new elements in the GMDSS (Global Maritime Distress and Safety System). The method proposed in this paper allows, without complex numerical applications and through common IT (Information Technology) tools, to determine communication ranges as a reverse process to determine the electric field strength as a function of distance. Section 2 presents a general propagation model to determine the electric field strength as a function of many variables, including the distance between antennas. Section 3 describes the method for range determination based on electric field strength values and provides example calculations. The results of the developed model for range determination were compared with the commonly used empirical model expressed in equation 3. Section 4 exemplifies the results presented in section 3 and indicates the practical application of the developed model for REMS.

Field strength and range calculations

The goal of the analysis is to determine the electric field strength in the free space e_0 (ITU-R P.525-3, 2016):

$$e_0 = 173 \frac{\sqrt{p}}{d} \tag{3}$$

where:
e_0 – r.m.s (root mean square) field strength [mV/m],
p – equivalent isotropically radiated power (e.i.r.p.) of the transmitter in the direction of ‘the point in question’ [kW],
d – distance from the transmitting and receiving antennas [km].

The transmission loss of the free space relative to the isotropic antenna L_{bf} is determined from the formula (ITU-R P.341-6, 2016):

$$L_{bf} = 32.4 + 20 \log f + 20 \log d \tag{4}$$

where:
f – frequency [MHz].

The total power losses between the transmitter and the signal receiver are determined based on the energy balance equation for a radio link (Saunders & Aragón-Zavala, 2007; Katulski, 2002; Instytut Łączności, 2005):

$$\left(P_t + G_t - L_t\right) - L - \left(P_r + G_r - L_r\right) = 0 \tag{5}$$

where:
P_t – transmitter output power [dBm];
P_r – power of the received signal [dBm];
L – losses on the way between antennas [dB];
L_t and L_r – losses in circuits of transmitting and receiving antennas, respectively [dB];
G_t and G_r – directivity gains of the transmitting and receiving antennas [dB].

In in ship-to-ship communication at sea, it is not necessary to consider the impact of terrain and buildings in the modeling process, but the effect of radio wave reflection on the sea surface (multipath propagation) must be taken into account. Multipath propagation results in signal losses due to direct wave interference and reflection from the sea surface. The worst situation occurs when there is no direct wave, and when a small number of reflected waves makes it highly likely that significant signal losses will occur. On the other hand, in the case of a disturbed sea when there are many reflections and the phases of individual components are random, the direct wave dominates, and the likelihood of large signal losses is low (Pawłowski, 2001; Instytut Łączności, 2006).

Since the most important task of the developed propagation model is to determine the maximum communication range, two of the basic phenomena that should be taken into account are the diffraction of the wave over obstacles and the spherical surface of the earth (ITU-R P.526-14, 2018). We should consider the radius of the Fresnel zone (Fresnel ellipsoid) R_n determined from the formula:

$$R_n = 550\left[\frac{n d_1 d_2}{(d_1 + d_2) f}\right]^{0.5} \tag{6}$$

where:

d_1, d_2 – the distances [km] between transmitter and receiver at the point where the ellipsoid radius [m] is calculated,

n – Fresnel ellipsoid number.

The obstacle taken into account in the diffraction analysis can be considered singular if the distance from the next obstacle d_t is less than 0.6 radius of the first Fresnel zone ($d_t < 0.6R_1$). The surface of the Earth can be considered smooth if the radius of the curvature of the terrain unevenness h_t is less than or equal to 0.1 the maximum radius of the first Fresnel zone in the propagation path d ($h_t < 0.1R_1$) (ITU-R P.1546-5, 2013). Later in the paper it is assumed that the surface of the terrain between the transmitting and receiving antennas is smooth because we consider the propagation over the sea surface.

The measure of field intensity losses due to diffraction is the ratio:

$$20 \log \frac{e}{e_0} = F(X) + G(Y_1) + G(Y_2) \tag{7}$$

where:

e – loss of field strength due to diffraction,

$F(X)$ and $G(Y)$ – functions depending on the distance between the transmitting and receiving antennas, respectively:

$$F(X) = 11 + 10\log(X) - 17.6X \quad \text{for } X \geq 1.6$$
$$F(X) = -20\log(X) - 5.6488X^{1.425} \quad \text{for } X < 1.6 \tag{8}$$

$$G(Y) \cong 17.6(B-1.1)^{0.5} - 5\log(B-1.1) - 8 \quad \text{for } B > 2$$
$$G(Y) \cong 20\log\left(B + 0.1B^3\right) \quad \text{for } B \leq 2 \tag{9}$$

where:

B – the parameter – Eq. (12),

X – the normalized length of the path between the antennas at normalized heights Y_1 and Y_2:

$$X = \beta\left(\frac{\pi}{\lambda a_e^2}\right)^{1/3} d$$
$$Y_i = 2\beta\left(\frac{\pi^2}{\lambda^2 a_e}\right)^{1/3} h_i \tag{10}$$

where:

i – antenna number: $i = 1$ transmitting antenna, $i = 2$ receiving antenna;

λ – wavelength [m];

h_i – the heights at which the transmitting and receiving antennas are mounted, respectively [m];

β – parameter which is the function of ground conductivity in the propagation path and antenna polarization (Table 1);

a_e – equivalent Earth's radius [km] (ITU-R P.310-9, 1994; ITU-R P.1812-4, 2015):

$$a_e = a\, k \tag{11}$$

where:

a – real earth radius ($a = 6371$ km);

k – effective earth radius factor.

Due to such a geometrical transformation, linear radius trajectories are obtained, regardless of the elevation angle. It can then be assumed that the propagation path is horizontal, and that the gradient of the atmosphere refraction is constant. For a height below 1000 m, the exponential model for the medium refractive index profile can be linearly approximated. The coefficient k is then $k = 4/3$ (ITU-R P.1812-4, 2015; ITU-R P.453-13, 2017; ITU-R P.834-9, 2017).

The parameter B from equation 9 is determined from the formula:

$$B = \beta\, Y_i \tag{12}$$

where β is determined according to the Table 1 or calculated from the formula:

$$\beta = \frac{1 + 1.6K^2 + 0.67K^4}{1 + 4.5K^2 + 1.53K^4} \tag{13}$$

where:

K – is a parameter dependent on the effective earth radius factor, frequency, and the conductivity of the sea which can be calculated based on the following formula:

$$K^2 \approx \frac{\sigma}{k^{2/3} f^{5/3}} \tag{14}$$

where:

σ – conductivity of the sea [S/m] (ITU-R P.368-9, 2007; ITU-R P.1812-4, 2015; ITU-R P.527-4, 2017).

Table 1. The dependence of the coefficient β on the antenna polarization and frequency (ITU-R P.526-14, 2018)

Polarization	Frequency & Terrain	β
horizontal	> 20 [MHz], land > 300 [MHz], sea	1
vertical	< 20 [MHz], land < 300 [MHz], sea	Function of K

Conductivity is a parameter that depends on the type and humidity of the ground on the propagation path and indirectly on the ambient temperature. Since communication in the VHF band occurs through surface waves over inhomogeneous terrain, there are rapid changes in the intensity of the field near the interface of areas with different conductivity.

Based on Eq. 3 to Eq. 14 we can write

$$e_0 = f(d, h_1, h_2, P_t, ...) \quad (15)$$

This relationship is non-linear and discontinuous.

Modeling – calculating the range of radio stations

Calculations of communication range in the marine VHF band using the mathematical model described in the paper consist of determining the distance d for which the field strength reaches the assumed value (1 or 2 µV/m for DSC and 2 µV/m for radiotelephony) (ITU-A.609, 2015). It requires, among others, the determination of field strength losses – Eq. (7). The values assumed by the $G(Y_i)$ function depend on the height of the transmitting and receiving antennas, ground conductivity, and frequency. The value of the function $F(X)$ depends on the wavelength and distance between the antennas. At the same time, according to Eq. (8) and Eq. (10), the form of the expression $F(X)$ which is used to calculate the communication range d is indirectly dependent on this distance. Thus, it is reasonable to treat the issue as an inverse problem. To solve this problem, we used the Generalized Reduced Gradient (GRG) method, which is applied to continuous problems. As shown by tests, the discontinuity expressed in Eq. (8) did not affect the calculation method used. To solve this problem, the non-linear optimization GRG method implemented in the "Solver" supplement to MS Excel can be used.

Table 2. Calculated ranges (in kilometers) of radiotelephony communication as a function of the height of transmitting h_1 and receiving h_2 antennas above the sea surface using Eq. (2)

h_1 [m]	h_2 [m]								
	10	20	30	40	50	60	70	80	90
10	29	35	40	44	47	50	53	56	58
30	35	41	46	50	53	56	59	62	64
50	47	53	58	62	65	68	71	74	76
100	61	67	71	75	79	82	84	87	90
200	80	86	90	94	98	101	104	106	109
500	117	123	128	132	135	138	141	144	146

Table 3. The radiotelephone communication ranges of the developed model as a function of the height of transmitting h_1 and receiving h_2 antennas above the sea surface

h_1 [m]	h_2 [m]								
	10	20	30	40	50	60	70	80	90
10	16	22	25	28	31	33	36	37	39
30	25	33	38	42	45	48	50	53	55
50	31	40	45	49	53	56	58	61	63
100	41	51	57	61	65	68	71	73	76
200	56	67	73	78	82	85	88	90	92
500	86	97	104	109	113	116	119	122	124

Table 4. The DSC communication ranges of the developed model as a function of the height of transmitting h_1 and receiving h_2 antennas above the sea surface

h_1 [m]	h_2 [m]								
	10	20	30	40	50	60	70	80	90
10	21	28	33	36	39	42	44	47	49
30	33	42	47	52	55	58	61	63	65
50	39	49	55	60	63	66	69	72	74
100	51	61	67	72	76	79	82	84	87
200	66	77	84	89	93	96	99	101	104
500	97	108	115	120	124	127	130	133	135

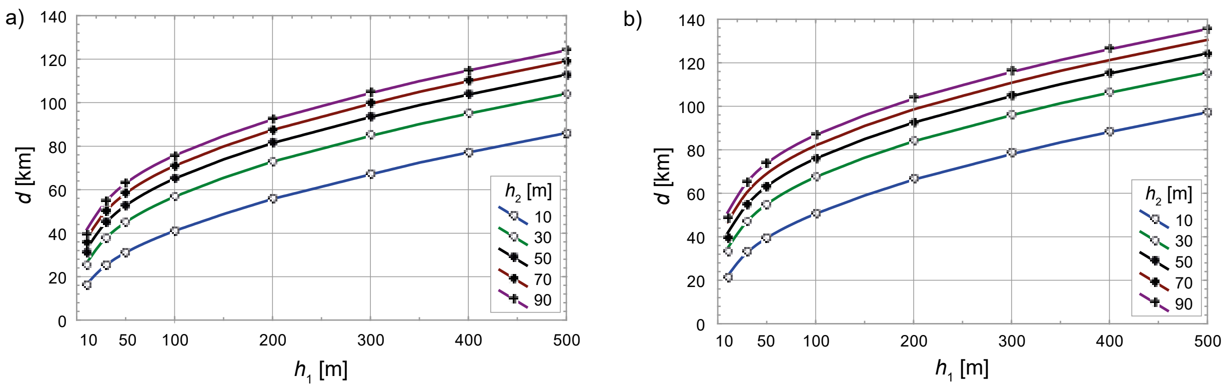

Figure 1. Communication ranges d [km] of the developed model as a function of the height of the transmitting h_1 and receiving h_2 antennas above the sea surface: a) for radiotelephony, b) for DSC

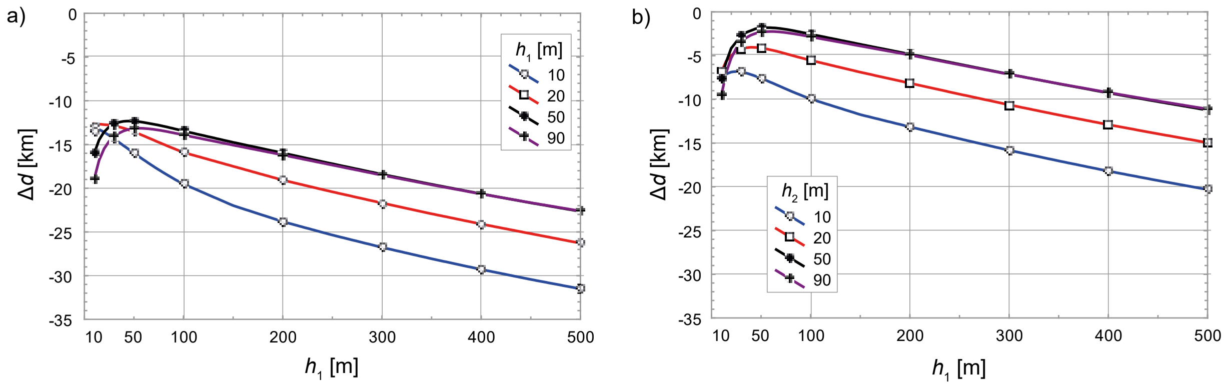

Figure 2. Communication ranges difference between of the developed model and empiric model as a function of the height of the transmitting and receiving antennas above the sea surface: a) for radiotelephony, b) for DSC

The radiotelephone coverage ranges determined using the developed model at a transmitting power P = 50 W shown in Table 3 are very close to the ranges determined from the empirical model by Eq. (2) (Table 2). However, the ranges assigned to DSC (Table 4) are from 9 to 34 percent greater than those for the radiotelephone.

For the developed model, the radio coverage ranges for radiotelephony and DSC versus antenna heights are presented in Figure 1. Figure 2 illustrates the range difference between the developed model and the empirical model based on Eq. (2) versus antenna heights.

The graphs indicate that the smallest difference between the developed model and the empirical model occurs at a transmitting antenna height of about 20 m. Differences between the developed model and the empirical model are practically constant when the height of the receiving antenna h_2 is greater than 50 m.

Examples of the range determination method

To present the effects of the developed method to determine ranges in the VHF band in Figure 3, an example situation is used in which there is an S0 shore station and two ship stations S1 and S2 for the most important frequencies f = 156.8 MHz in the maritime VHF band. The assumed height of the shore station antenna is h_1 = 200 m, for ship S1 h_2 = 40 m, and for ship S2 h_2 = 10 m. The continuous line indicates radiofrequency ranges determined according to the empirical formula Eq. (2) and the dotted line represents that obtained from the model presented in this paper. The radii of the circles for the shore stations S0 (after considering a transmitting power P_t = 50 W) shall be 56, 78, 80, and 94 km and for ships S1 and S2 (at a transmitting power P_t = 25 W), 29 and 37 km, respectively. It can be seen in the illustration that the shore station can radio-connect with ships S1 and S2 in the maritime VHF band according to Eq. (2) developed by the empirical method, but it cannot connect according to the model developed in the paper. For ships S1 and S2, there will be no radio range between them according to the developed model, but according to the empirical model, a radio range would be ensured.

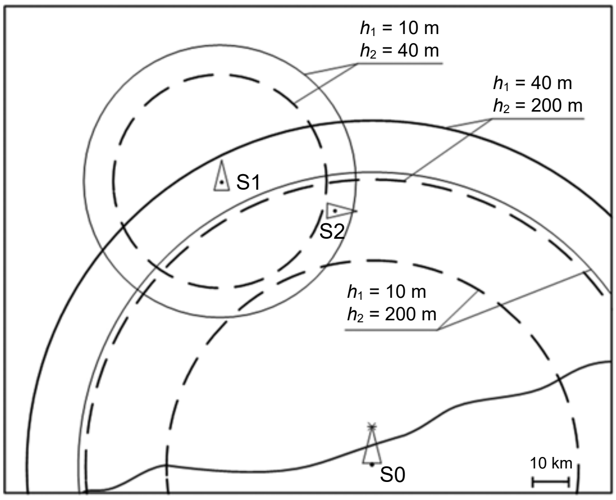

Figure 3. Deployment and ranges of radio stations in sea area A1. The continuous line indicates empirical ranges. The dotted line indicates developed model ranges

Tables 5 and 6 show the matrix of information reception availability for the empirical (Majzner & Mąka, 2014, Mąka & Majzner, 2017) and developed models, respectively.

Differences between the information availability matrices presented in Tables 5 and 6 may influence the decision-making process of the shore and ship station operators, depending on which propagation model is used.

Table 5. Matrix of the information reception availability determined for the empirical model

	S_0	S_1	S_2
S_0	1	1	1
S_1	1	1	1
S_2	1	1	1

Table 6. Matrix of the information reception availability determined for the developed model

	S_0	S_1	S_2
S_0	1	0	0
S_1	0	1	0
S_2	0	0	1

Conclusions

This article presents an analytical model of propagation in sea area A1, which is a REMS component. The authors propose a method to calculate ship and coast radio stations ranges in sea area A1. Based on the article, the following conclusions can be made:

- The developed model due to the inclusion of many parameters of the transmitted signal more closely represents reality than the empirical model.
- The smallest difference between the developed model and the empirical model occurs when the height of the transmitting antenna h_1 is about 20 m.
- The empirical models developed in this article give similar values of ranges when the heights of transmitting and receiving antennas do not differ significantly.
- The developed model also allows the range for DSC to be determined, which is not possible using the empirical model.
- The ranges determined using the developed model allow for a more adequate determination of the value of the information availability matrix and, consequently, a more accurate modelling of communication events at sea.

The advantages of the developed method to determine ranges between two stations operating in the VHF band offer a more accurate analysis of the decision-making processes involving radio operators, which in turn may lead to a more accurate development of the decision support system of GMDSS radio operators on ships.

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