**ARI** The Bulletin of the Istanbul Technical University VOLUME 54, NUMBER 2
Communicated by Sondan Durukanoğlu Feyiz

# Ground Wave Attenuation Curves in the Presence of Successive 2-D Islands

Burak Polat
*Department of Electronics and Communications Engineering, Istanbul Technical University, 34469 Maslak, Istanbul, Turkey*
(Received 11 February 2004)

Numerical solutions are presented for the formulation given by Furutsu in calculating the transmission loss of HF ground wave radar/communication systems in the presence of successive 2-D islands aligned along the propagation path. The curves for the variation of the ground wave attenuation factor with the operation frequency and the number and the size of the 2-D canonical island models yield us important hints about the total transmission loss one should expect in the design of HF ground wave radar/communication systems.

**Keywords:** HF ground wave radar, ground wave propagation, transmission loss, surface irregularities.

## 1. Introduction

Propagation of radiowaves over ground has been subject to many investigations since the pioneering work of Sommerfeld [1] in 1909, in which he presented the formal solution for the electromagnetic field generated by a vertical electric dipole located over homogeneous earth. Roughly we can classify all sets of solutions according to the methods employed as analytical/asymptotic, numerical, empirical and hybrid ones. Among a number of empirical solutions, Millington's method [2,3], which employs the reciprocity principle, is known to give the best fit, especially in the HF band ($3-30$MHz), to measurement data and analytical reference solutions. The numerical methods based on discretization, on the other hand, all suffer from excessive computation time considering ranges/distances of thousands of wavelengths. Therefore analytical/asymptotic methods are mostly preferred for providing range independent solutions and generally classified according to the operation frequency being “high” or “low”.

The presence of irregularities or obstacles along the propagation path gives rise to a considerable amount of signal distortion and loss at the receiver and are analyzed using different analytical/asymptotic methods for an accurate solution. Among them are integral equation solutions efficient in low frequencies, high frequency asymptotic methods based on geometrical or physical optics, and of course, hybrid ones for best convergence depending to the structure of the inhomogeneity. In the HF band one may mention particularly to three different methods met frequently in the literature; namely, electromagnetic compansation theorem by Monteath [4], mode matching approach based on creeping wave representation by Wait [5], and the integral equation formulation method of Furutsu [6]. All three methods are discussed in great detail in the literature and yield identical analytical results in the special case of a planar discontinuity, despite originating from different techniques. Among them the Green's function formulation of Furutsu, despite the highly sophisticated theory that lies under, seems to be the most suitable one for investigating ground wave propagation through a succession of large and wide terrain features since the series representation of the total field in each section is quite available and efficient for computation. This paper is concerned with the ground wave attenuation in the HF band due to successive isolated terrains, i.e., “islands” aligned along the propagation path. A number of curves for the variation of the ground wave attenuation factor with the operation frequency and the number and size of the 2-D canonical island models are depicted. Results yield us important hints about the transmission loss one should expect in the design of HF ground wave radar/communication systems.

A time convention $\exp(i\omega t)$ is assumed and suppressed throughout the work.

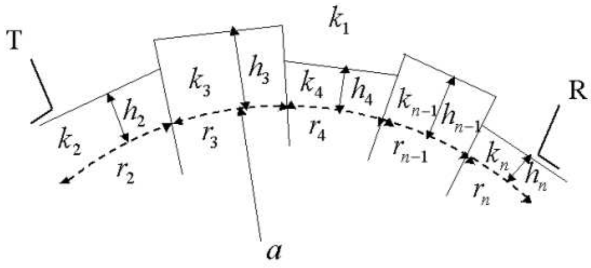


Figure 1. The mathematical model of a land based T/R antenna system and the terrain consisting of a number of sections. (The figure is taken from [11] with some changes).

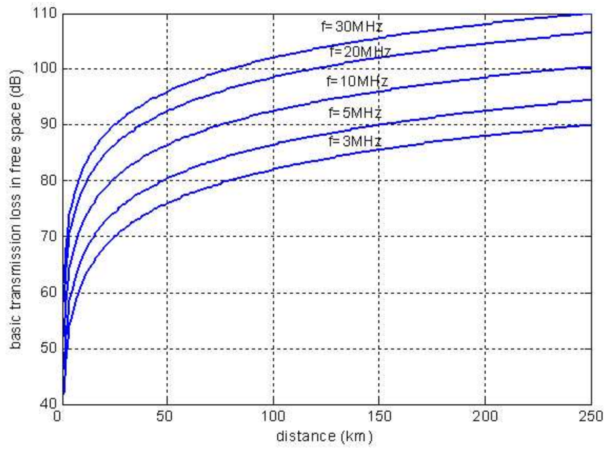


Figure 2. The variation of the basic transmission loss in the HF band for different frequencies.

## 2. Formulation

The canonical irregular terrain model by Furutsu treats earth's surface as composed of a number of successive terrains in the shape of flat topped dielectric sections with vertical sides each having arbitrary height and length. The length of the body is large enough compared to the operation wavelength in accordance with the Fresnel-Kirschoff approximation, i.e., the formulation does not take into account the possible wave components which are reflected several times between the two boundaries of the sections (see Fig. 1). The sharp straight lines in the model disregard perturbations small in terms of operation wavelength ( $\lambda$ between $10-100$m) in the actual profile of an island in order to make the problem attainable by analytical methods. The "2-D" approximation also implies that the widths of the islands are long enough in terms of operation wavelength so that any contribution from the part of the energy that reaches at the receiver by circling around the island is neglected. Despite the physical and geometrical constraints imposed for describing a canonical problem, the reduced structure is still highly flexible and suitable to represent terrains containing ridges, bluffs, coastlines with cliffs, and has been investigated in numerous papers by Furutsu [6–11].

The well-known ground wave (Sommerfeld) attenuation factor is given by Furutsu as [11]

$$F(r)=\begin{cases}\sum\limits_{t_2}\Phi, & 0<r<r_2\\ \sum\limits_{t_3,t_2}\beta, & r_2<r<r_2+r_3\\ \cdots\cdots\cdots\cdots\cdots\cdots & \\ \sum\limits_{t_n,\ldots,t_3,t_2}\varphi, & r_2+r_3+\ldots+\\ +r_{n-1}<r<r_2+r_3+\ldots+ & \\ +r_{n-1}+r_n & \end{cases}\tag{1}$$

where

$$\begin{aligned}\Phi &= c_2^{1/2}f_{t_2}(y_{32})A_{t_2}(c_2)f_{t_2}(y_{12})\\ \beta &= (c_3+c_2)^{1/2}f_{t_3}(y_{43})A_{t_3}(c_3)T_{t_3,t_2}(c_2)\times\\ &\times\ f_{t_2}(y_{12})\\ \varphi &= (c_n+\ldots+c_3+c_2)^{1/2}f_{t_n}(y_{n+1,n})\times\\ &\times\ A_{t_n}(c_n)T_{t_n,t_{n-1}}(c_{n-1})\cdots T_{t_3,t_2}(c_2)\times\\ &\times\ f_{t_2}(y_{12})\end{aligned}\tag{2}$$

In (1) $T_{t_j,t_{j-1}}(c_{j-1})$ and $A_{t_j}(c_j)$ correspond, respectively, to the effect of propagation along $(j-1)$-th and $j$-th sections to total attenuation, and are given explicitly by

$$\begin{aligned}&T_{t_j,t_{j-1}}(c_{j-1})=(y_j-y_{j-1}+t_j-t_{j-1})^{-1}\times\\ &\times\exp\{-i[c_{j-1}(t_{j-1}+y_{j-1})]\}\times\\ &\begin{cases}q_jf'_{t_j}(y_{j-1,j})-q_{j-1}f_{t_j}(y_{j-1,j}),\ y_{j-1}\geq y_j\\ q_jf_{t_{j-1}}(y_{j,j-1})-q_{j-1}f'_{t_{j-1}}(y_{j,j-1}),\ y_{j-1}\leq y_j\end{cases}\end{aligned}\tag{3}$$

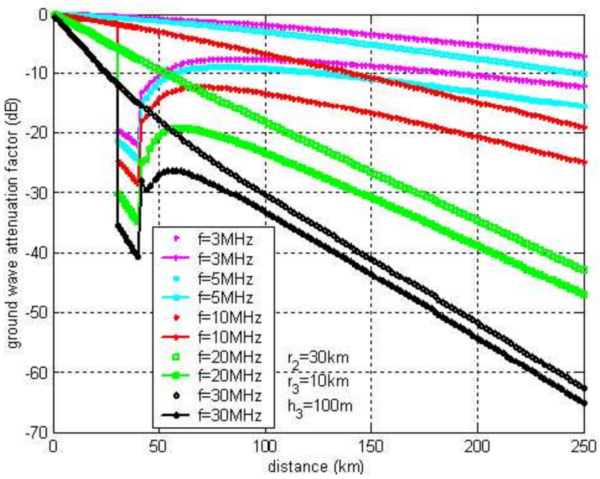


Figure 3. The variation of the ground wave attenuation factor with distance in the HF band for different frequencies in the presence of a single island ($h_2 = h_4 = 0$m).

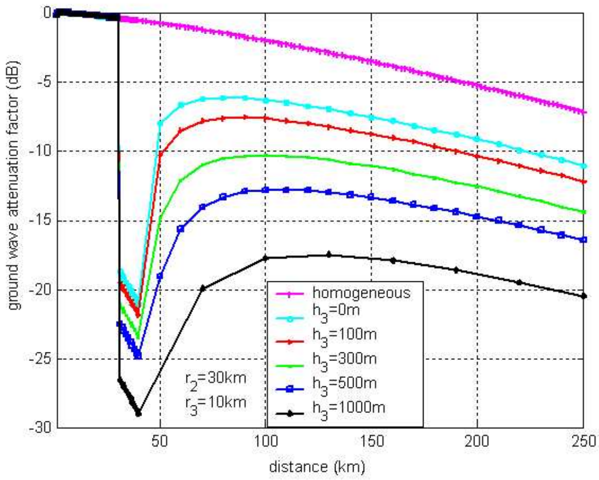


Figure 4. The variation of the ground wave attenuation factor with distance in the HF band for different heights in the presence of a single island ($f = 3$MHz, $h_2 = h_4 = 0$m).

$$A_{t_j}(c_j) = \sqrt{\pi}(t_j - q_j^2)^{-1} \times \times \exp\{-i[c_j(t_j + y_j) + \pi/4]\} \quad (4)$$

$k_1$ is free space wavenumber and $k_j$, $j = 2, \ldots, n$ stands for the wavenumber of the $j$-th section. $a = (4/3) \times 6378$km corresponds to the effective radius of earth when we take into account the first order tropospheric refraction. $c_j$ and $y_j$, $j = 2, \ldots, n$ are related to the path length $(r_j)$ and height $(h_j)$ of the $j$-th section and given by

$$c_j = \frac{r_j}{a}\left(\frac{k_1 a}{2}\right)^{1/3} \quad (5)$$

$$y_j = k_1 h_j \left(\frac{2}{k_1 a}\right)^{1/3} \quad (6)$$

with $y_{lm} = y_m - y_l$. $h_1$ and $h_{n+1}$ stand for the heights of the T/R Hertzian dipoles over ground. Note that $h_1 = h_{n+1} = 0$ for land-based T/R antennas.

Height gain functions are given by

$$f_{t_j}(y_{j-1,j}) = W(t_j - y_{j-1,j})/W(t_j) \quad (7)$$

$$f'_{t_j}(y_{j-1,j}) = W'(t_j - y_{j-1,j})/W'(t_j) \quad (8)$$

where $W(t) = \sqrt{\pi}[\mathrm{Bi}(t) - i\mathrm{Ai}(t)]$ is expressed in terms of standard Airy functions. $t_j(s)$, $s = 1, 2, \ldots$ is the set of simple roots of infinite number of the equation

$$W'(t_j) - q_j W(t_j) = 0 \quad (9)$$

with

$$q_j = -i\left(\frac{k_1 a}{2}\right)^{1/3} \Delta_j \quad (10)$$

$$\Delta_j = k_1(k_j^2 - k_1^2)^{1/2}/k_j^2 \quad (11)$$

These roots correspond to the eigenvalues of the ground wave modes, lie on the fourth quadrant of the complex plane, and increase with magnitude with index $s$. $q_j$ and $\Delta_j$ are called ground constant for vertical polarization and the normalized surface impedance of the $j$-th terrain, respectively.

Among a number of different algorithms for determining the eigenvalues the one described in [12, pp. 340–343] is seen to be the most accurate and valid for a wide range of frequencies and ground constants.

The equation for the transmission loss between two land based quarterwave whip antennas at a distance $r$ is given by [13, 14]

$$L_s = L_f - G'_T - G'_R - 20\log_{10}|F(r)| - 6.02 \quad (12)$$

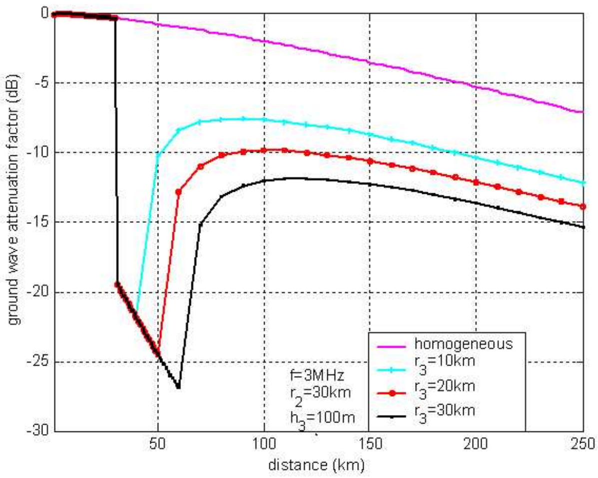


Figure 5. The variation of the ground wave attenuation factor with distance in the HF band for different widths in the presence of a single island ($h_2 = h_4 = 0$m).

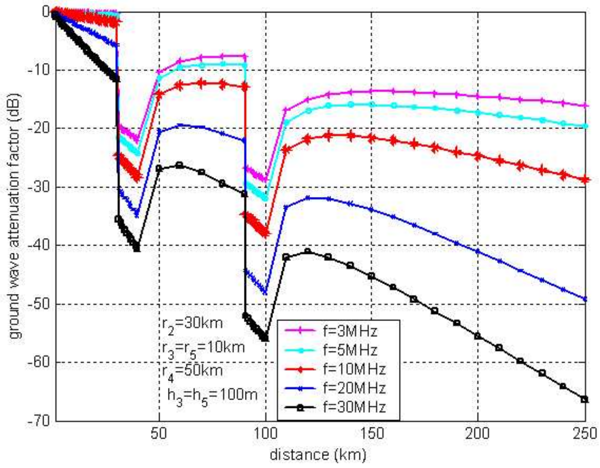


Figure 6. The variation of the ground wave attenuation factor with distance in the HF band for different frequencies in the presence of two islands ($h_2 = h_4 = h_6 = 0$m).

Table 1
The calculation of $L_f(dB)$ and $F(dB)$ at a range of 250km.

| $f$[MHz] | $L_f(dB)$ | $F^{(1)}(dB)$ | $F^{(2)}(dB)$ | $F^{(3)}(dB)$ |
|---|---|---|---|---|
| 3 | 90 | $-12$ | $-16$ | $-20$ |
| 10 | 100 | $-25$ | $-29$ | $-32$ |
| 20 | 106 | $-47$ | $-49$ | $-51$ |
| 30 | 110 | $-65$ | $-66$ | $-68$ |

Table 2
The calculation of $L_s(dB)$ at a range of 250km.

| $f$[MHz] | $L_s^{(1)}(dB)$ | $L_s^{(2)}(dB)$ | $L_s^{(3)}(dB)$ |
|---|---|---|---|
| 3 | 98 | 102 | 106 |
| 10 | 121 | 125 | 128 |
| 20 | 149 | 151 | 153 |
| 30 | 171 | 172 | 174 |

In (12) $L_f = 20\log_{10}(4\pi r/\lambda_1)$ is the basic transmission loss in free space with $\lambda_1$ being the operation wavelength, and $G'_T = G'_R = -0.86dB$ [14] correspond to the effective gains of the T/R antennas located on a perfectly conducting ground plane.

## 3. Numerical Illustrations

In this section we will present a number of curves and tables to emphasize the importance of ground wave attenuation mechanism in the design of HF ground wave radar/communication systems in the presence of a succession of islands. The constitutive parameters for the land sections and smooth sea are taken as ($\varepsilon_r = 15$, $\sigma = 10^{-3}$ S/m) and ($\varepsilon_r = 80$, $\sigma = 4$ S/m), respectively. For comparison basic transmission loss curves are also depicted in Fig. 2.

In Fig.s 3-9, the unbroken lines correspond to the expected values when the island(s) is(are) removed. The effects of operation frequency, the height and width of the islands on ground wave attenuation are depicted in Fig.s 3,4 and 5 for a single island. Though a small number of numerical solutions for this special geometry have been presented in a paper by Furutsu [9, Fig.s 10a-d] for a set of parameters, they are recalculated in this work for a different set of parameters to see the picture as a whole when we consider a succession of islands. The dramatic increase in loss with the operation frequency for $f > 10$MHz and the well-known recovery effect that occurs after land to sea transitions are clearly observed. High losses with the operation frequency and island height are due to the sharp vertical faces of the island. In this regard this mechanism is quite

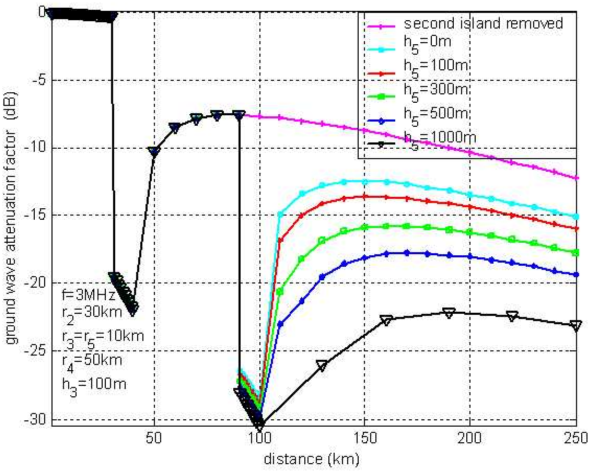


Figure 7. The variation of the ground wave attenuation factor with distance in the HF band for different heights of the second island ($h_2 = h_4 = h_6 = 0$m).

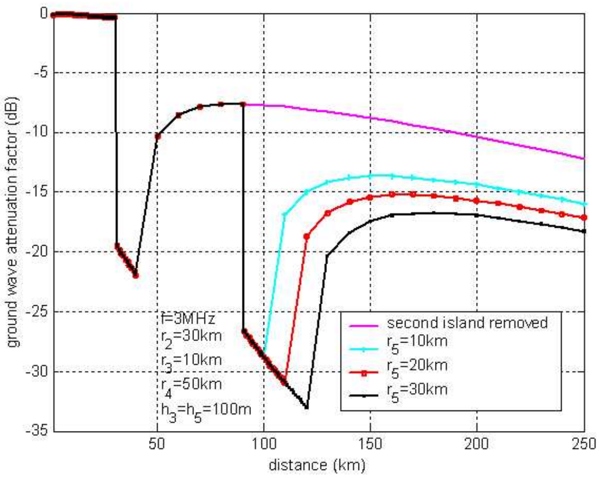


Figure 8. The variation of the ground wave attenuation factor with distance in the HF band for different widths of the second island ($h_2 = h_4 = h_6 = 0$m).

different than that calculated by Wait [19] for circular islands with smooth height profile under the Born approximation.

Fig.s 6–9 illustrate the effect of a second and a third island along the propagation path. As far as the author is concerned such curves do not appear in literature though they are of high importance for radar and communications engineers in the calculation of the required dynamic range of the receiver system. It should be noted that the convergence of the multiple series is rapid at points away from the immediate vicinity of the boundaries.

Tables 1 and 2 show the basic transmission loss $L_f(dB)$, the ground wave attenuation ($F^{(1)}$, $F^{(2)}$, $F^{(3)}$), and the total transmission loss ($L_s^{(1)}$, $L_s^{(2)}$, $L_s^{(3)}$) calculated at a range of 250km in the presence of a single, two and three island(s) aligned along the path, each having a width of 10km, a height of 100m, and starting at $r = 30$km, 90km, and 150km.

Note that for radar operations the total transmission loss is almost twice the values given in Table 2.

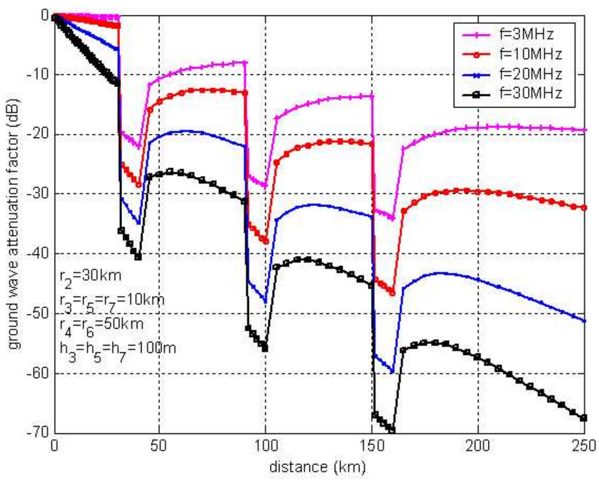


Figure 9. The variation of the ground wave attenuation factor with distance in the HF band for different frequencies in the presence of three islands ($h_2 = h_4 = h_6 = h_8 = 0$m).

## 4. Concluding Remarks

In this paper the formulation of Furutsu is applied to enlighten the mechanism of ground wave attenuation in the presence of successive islands aligned along the propagation path. A number of curves and tables are presented to comprehend the dependence of the transmission loss on the operation frequency and the number of "islands". Note that the formulation is capable of simulating the attenuation due to earth's curvature, antenna heights, surface roughness (due to the sea spectrum) [16, 17] by modifying $\Delta_j$ in (11), tropospheric refraction, and hopefully, ionospheric effects via the earth-ionosphere waveguide model of Wait [18, 19] as well. Of course, the validity of these curves, no matter how reasonable they may look, needs to be confirmed with real data before one can get use of them in planning an actual radar/communication system. As far as the author is concerned, published real data verifications or mixed path ground wave propagation in the HF band are available only for the limiting case when the island height tends to zero [3]. One may also mention to the laboratory measurements done by R.J. King and his colleagues [20–24] by rescaling the problem of planar discontinuity up to microwave bands.

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