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TOWARDS A BETTER EXCITATION OF THE SURFACE WAVE

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Abstract—In the field of maritime surveillance, HF surface wave radars seem to be considered as an optimum and low cost solution. Nevertheless, the commonly used radiating elements of those radars are not yet able to only launch surface waves. We aim to design a specific radiating element optimized for exciting such waves. The first step of such an issue is to set thoroughly the problem. In this paper, surface waves on the boundary between two dielectric media are considered. Kistovich decomposition is applied in order to discuss the influence of the Zenneck wave on the field excited at the sea surface. It is shown that Zenneck approach and Norton's one are not contradictory. Above all, we point out that, using Kistovich decomposition to design radiating elements, we can expect a significant improvement of the surface wave intensity.

1. INTRODUCTION

In the last decades, maritime surveillance has never stopped gaining interest. Since 1982, when the United Nations Convention on the Law of the Sea has been signed, states can extend their rights over the exploitation and use of maritime resources up to 200 nautical miles from their coasts. This zone is called the Exclusive Economical Zone (EEZ). However, its surveillance remains quite difficult: on the one hand, coast extension makes the surface so wide that a system of airborn radars is unpractical, but, on the other hand, land based radars

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are limited by the radio electric horizon. Other solutions like satellites are too expensive and cannot guarantee a constant control nor a high resolution. The optimum solution is the so called Surface Wave Radar: operating at HF frequencies, this land based radar utilizes surface wave propagation and is not affected by radio electric horizon [1]. However, its primary weakness lies in the antennas used for the excitation of the surface field, because a considerable amount of energy is spread towards the sky. This means that, not only the efficiency of the surface wave radar is strongly depreciated (i.e., radiated energy is not totally exploited by the surface wave radar), but, at the same time, signal processing complexity is raised (i.e., sky wave causes ionospheric clutter from time to time) [2].

The strong expectation concerning the HFSWR in border security or maritime surveillance [3] encourages us to search how to radiate surface waves only. As a consequence, we will improve the coverage and reduce the processing intricacy. Such an objective could not be reached if the surface wave problem is ill-posed.

In the High Frequency band (i.e., between 3 MHz and 30 MHz), electromagnetic waves have the capability of being guided by the surface of the sea. Since sea water at HF frequencies can be seen as a lossy conductor, surface wave is vertically polarized and vertical wire antennas, located close to the sea, are often used to excite it. Many studies, both theoretical and practical, have been led to determine the characteristics of the fields radiated by a wire antenna above a lossy conductor: we can cite seminal works by Zenneck, Sommerfeld, Norton, Burrows, Bremmer, Fock and Wait (for a complete bibliography on the subject, please refer to [4]).

Surface Wave history began with the theoretical proof given by Zenneck that the plane discontinuity between two semi-infinite media (a lossy conductor and a dielectric medium) supports an evanescent wave mode, called Zenneck Wave. This wave, when sea and air are considered at HF frequencies, has a very slow decaying rate along the sea surface and a very fast decaying one in the direction normal to the interface: this peculiarity made the radio-wave community at the beginning of the 20th century believe that transoceanic communications were possible thanks to Zenneck Wave [5]. However, they were wrong: an error sign in Sommerfeld's paper was the cause of years of misunderstandings [4, 6]. More recent studies provide the correct expressions of the field excited on the sea surface by a source placed in its vicinity [7], while the existence of a pure Zenneck wave is still discussed [8, 9]. Moreover, if Earth sphericity is taken in account, surface wave follows Earth bend, allowing radio-electric system to convey an amount of energy beyond the horizon [10].

Although Zenneck approach is long-established, we are showing here how Zenneck wave isolation is a necessary step in the formulation.

In this paper, after a short recall of Zenneck wave and Norton surface wave concepts, we go into detail about the Kistovich decomposition of the field excited by an infinite source at the interface between two dielectric media. This decomposition permits, in a simple way, to isolate Zenneck wave contribution from the total field. In the last section, we will show that it is possible to correlate this theoretical infinite source configuration with a more realistic one using a quasi-infinite array of vertical dipoles. Furthermore, this method will help to increase the part of the electric field radiated as a surface wave.

2. GEOMETRY AND NOTATIONS

Through this paper, we will refer to the geometry and the coordinate systems depicted in Fig. 1. Medium 1 ($z > 0$) is assumed to be free space with a propagation constant $k_0 = 2\pi f\sqrt{\mu_0\varepsilon_0}$, where f is the wave frequency. Medium 2 ($z < 0$) has a complex dielectric constant $\underline{\varepsilon} = \varepsilon_0\underline{\varepsilon}_r$ such that $|\underline{\varepsilon}_r| \gg 1$ and the same permeability as that of free space. The time factor has been chosen as $e^{-i2\pi ft}$ and it will be omitted everywhere.

Related to the surveillance of the EEZ, medium 2 will be assumed to be sea water of permittivity $\underline{\varepsilon}_r = \varepsilon_r' + i\frac{\sigma}{\varepsilon_0 2\pi f}$, with $\varepsilon_r' = 81$ and conductivity $\sigma = 5\,\mathrm{S/m}$.

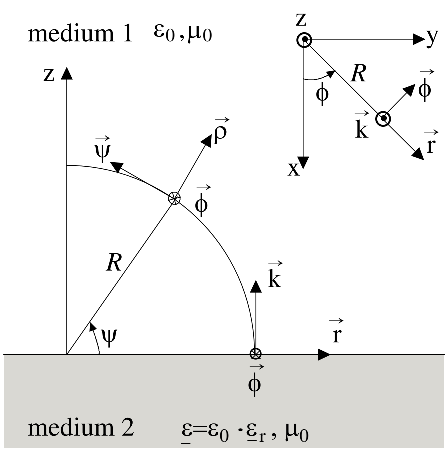

Figure 1. Geometry under investigation in the case of a plane interface.

3. CLASSIC SOLUTIONS

In this section, we will consider two classic electromagnetic problems concerning the geometry described in the last paragraph. Firstly, we will examine a particular solution of Maxwell's equations, the Zenneck wave, excited by a source located far outside the studied region. Secondly, we will recall the expressions of the field excited by a Hertzian dipole located at the interface, at the origin of the axis system.

3.1. Zenneck Wave

Applying boundary conditions at $z = 0$ and imposing also boundary conditions at infinity in order to prevent the field from diverging, we can write the vertical component of a vertically polarized electric field, propagating along the x axis. This particular solution is historically called Zenneck wave. So we have:

$$E_{z1} = Ae^{ik_x x}e^{ik_{z1}z} \quad z > 0 \tag{1}$$

$$E_{z2} = Ae^{ik_x x}e^{ik_{z2}z} \quad z < 0 \tag{2}$$

where

$$k_{z1}^2 = \frac{1}{1+\underline{\varepsilon}_r}k_0^2 \tag{3}$$

$$k_{z2}^2 = \frac{\underline{\varepsilon}_r^2}{1+\underline{\varepsilon}_r}k_0^2 \tag{4}$$

and

$$k_x^2 = \frac{\underline{\varepsilon}_r}{1+\underline{\varepsilon}_r}k_0^2 \tag{5}$$

Quantity A in Equations (1) and (2) is the amplitude of the field, is expressed in V/m and depends on the source, which is unknown. As it can be seen from Equation (5), the Zenneck wave is a fast one. The interest in the Zenneck wave is about its properties at HF frequencies when propagating along the sea surface: the field is strongly concentrated near the interface, i.e., it decays fast in the z direction, while it is attenuated slowly in the x direction (Fig. 2).

3.2. Norton Surface Wave

We consider the classic problem of the field radiated by a Hertzian dipole located at the origin of the spherical coordinate system of Fig. 1. The solution, given by K. A. Norton, has the advantage of being easily interpreted. The author, in numerous papers (for example [7]), gives the expressions in the upper medium of the fields excited by electric

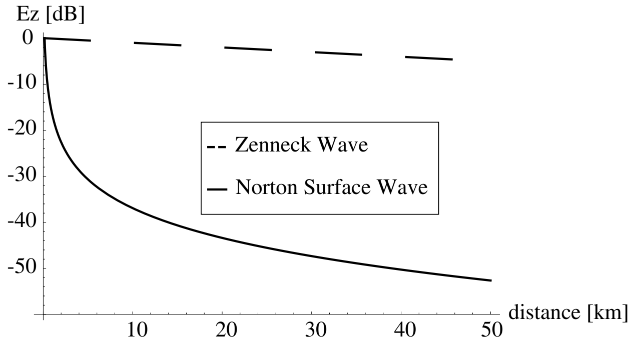

Figure 2. Attenuation of electric field's vertical component for Zenneck wave and Norton surface wave at $f = 10\,\mathrm{MHz}$. Fields are normalized to their values at $R = 5\lambda$.

or magnetic dipoles located at the interface or above it. Since we want to attract the reader's attention on the field excited by a Hertzian vertical dipole at the interface ($\Psi = 0$), we will only recall equations that permit to calculate it. Then, if we call with I_{ds} the dipole moment, the vertical component of the electric field vector at the interface is:

$$E_z(R) = \mathrm{i} I_{ds} f \mu_0 F \frac{\mathrm{e}^{\mathrm{i}(k_0 R)}}{R} \tag{6}$$

where

$$F = 1 + \mathrm{i}\sqrt{\pi w} e^{-w} \mathrm{erfc}\left(-\mathrm{i}\sqrt{w}\right) \tag{7}$$

$$w = \frac{1}{2} \mathrm{i} k_0 R u^2 \left(1 - u^2\right) \tag{8}$$

$$u^2 = \frac{1}{\varepsilon_r' + \mathrm{i}x} \tag{9}$$

$$x = 1.8 \cdot 10^{10} \frac{\sigma}{f} \tag{10}$$

The field expressed by these equations, widely confirmed by measurements [11] is commonly called a Norton Surface Wave. Its attenuation with the distance is plotted in Fig. 2.

For elevation angles greater than zero, a sky wave is also excited [7]: this sky-wave predominates over the surface wave at large distance. Then, comparing the results shown in Fig. 2, it appears that the best solution, for EEZ surveillance application using surface wave radar, is to design a launcher of Zenneck type wave.

The next section describes an original way followed to maximize this surface wave against the sky wave.

4. MODAL DECOMPOSITION

In order to study the contribution of the Zenneck wave to the field excited by a real source, we consider the modal decomposition introduced by Kistovich [12]. For a y-homogeneous, z directed current density, $\vec{J} = I(z)\delta(x)\hat{z}$, in the presence of a conducting half-space, the electromagnetic field will be of TM type. Using the surface impedance approximation ($Z = \mu_0/\sqrt{\varepsilon_0\varepsilon_r}$), a dispersion relation for the wave number in the z direction is achieved. A simple analysis of this dispersion relation permits to write the vertical component of the electric field as a sum of a Zenneck wave and an infinite spectrum of bulk waves:

$$E_z(x,z) = A_{Ze}e^{\mathrm{i}k_{Ze}z}e^{\mathrm{i}\sqrt{k_0^2-k_{Ze}^2}x} + \int_0^\infty A_b(p)e^{\mathrm{i}pz}e^{\mathrm{i}\sqrt{k_0^2-p^2}x}dp \qquad (11)$$

where

$$k_{Ze} = -\omega\varepsilon_0 Z \qquad p \in \mathbb{R} \qquad (12)$$

In particular, Equation (13) gives the expression of the vertical component of the electric field for $I(z) = I_{ds}\delta(z)$.

$$\begin{aligned} E_z &= \frac{\mathrm{i}I_{ds}k_{Ze}}{\omega\varepsilon_0}\sqrt{k_0^2-k_{Ze}^2}e^{\mathrm{i}\sqrt{k_0^2-k_{Ze}^2}x}e^{\mathrm{i}k_{Ze}z} \\ &\quad -\frac{I_{ds}}{\pi\omega\varepsilon_0}\int_0^\infty \frac{\sqrt{k_0^2-p^2}p^2e^{\mathrm{i}\sqrt{k_0^2-p^2}x}e^{\mathrm{i}pz}}{p^2-k_{Ze}^2}\,dp \end{aligned} \qquad (13)$$

In Fig. 3, we have plotted the behavior of the vertical component of the electric field, at $z = 0$, with the distance. The magnitude of the total resulting field is perfectly superposed to the bulk wave component and it is not influenced by the Zenneck wave, which is therefore totally hidden. This is due to the fact that these two contributions are out of phase. The attenuation figure of the total field is similar to the Norton wave, even if it has a slower decay.

From the orthogonality conditions on the basis functions, Kistovich showed that the sole case able to make Zenneck wave appearing without exciting bulk waves is to use an infinite vertical source.

Nevertheless, in the next section we will deal with two quasi-infinite arrays of Hertzian dipoles. The objective is double: firstly we want to relate the modal approach, effective with unrealistic sources, to the Norton wave, existing for real radiators. Secondly, we will show that a realistic, but still unrealizable, source can make the Zenneck wave appear.

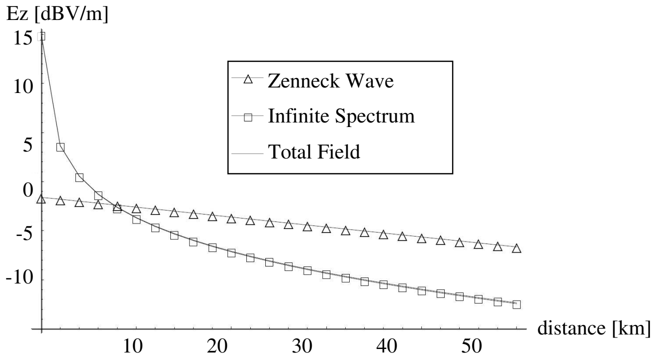

Figure 3. Decomposition of the field excited by a homogeneous current density on the sea surface at $f = 10\,\mathrm{MHz}$.

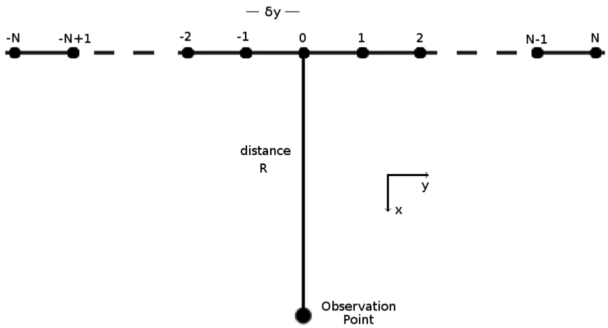

Figure 4. Geometry of the considered array.

5. DISCRETE LINE CURRENTS

In order to correlate the modal decomposition with the more realistic Norton approach, we have simulated two quasi-infinite arrays of Hertzian dipoles using the field expression of Equation (6). In a first step (see Fig. 4), each of the $2N + 1$ elements of the array will be a Hertzian dipole, while in a second step every radiator will be replaced by several Hertzian dipoles in order to discretize a vertical continuous current density distribution (see Fig. 5). The $2N + 1$ elements are spaced by a constant $\delta y = \lambda/2$ step, with $\lambda = 2\pi/k_0$. Possible couplings are neglected.

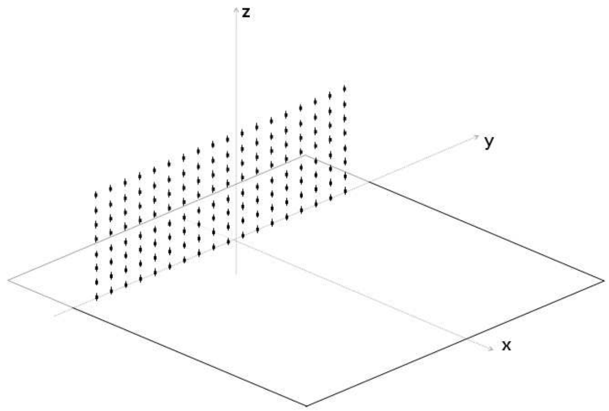

Figure 5. Geometry of the vertical current array. Each line is constituted by a number of vertical Hertzian dipoles in order to discretize the vertical current distribution.

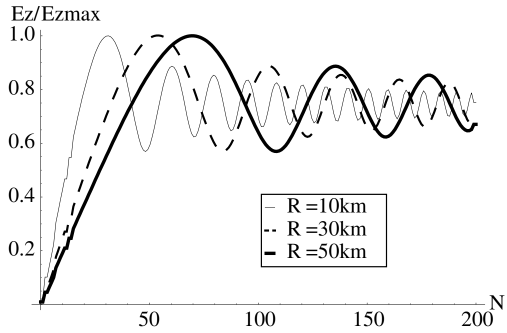

Figure 6. Oscillations of the vertical component of the electric field with the number of dipoles constituting the quasi-infinite array. The calculations are performed at the interface for $f = 10\,\mathrm{MHz}$. Fields are normalized to their maximum value Ezmax.

5.1. Hertzian Dipoles Array

As Kistovich's source has an infinite length along the y-axis, N should be chosen large enough. Fig. 6 shows the influence of N on the vertical component of the electric field, calculated at the interface for various distances from the array. As distance increases, N has to increase too in order to reach the asymptotic value of the field representative of the quasi-infinite configuration. In accordance with the results depicted in Fig. 6, we have chosen $N = 2000$ to avoid incertitudes due to oscillations.

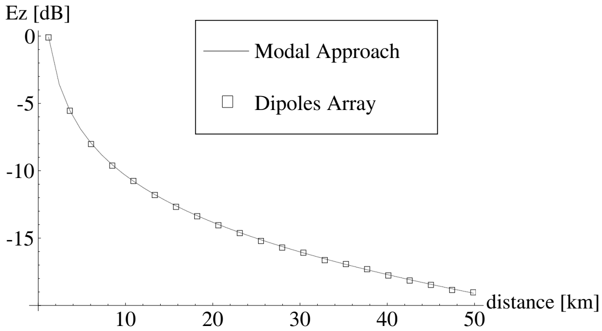

Figure 7. Vertical component of the electric field radiated by the dipole array ($N = 2000$, $\delta y = \lambda/2$) and by a current density $\vec{J} = I_{ds}\delta(x)\delta(z)\hat{z}$. The calculations are performed at the interface for $f = 10\,\text{MHz}$. Fields are normalized with their values at $R = 30\lambda$.

We have plotted in Fig. 7 the decay of the vertical component of the electric field excited by the quasi-infinite array and by the y-homogeneous line current $\vec{J} = I_{ds}\delta(y)\delta(z)\hat{e}_z$ (in accordance with Kistovich approach). It can be seen that the results are in perfect agreement with the results obtained using the modal approach. Thus, for finite observation distances, the y-homogeneous current can be synthetized by a semi-infinite array of Hertzian dipoles.

5.2. Discrete Vertical Current Array

We have stated in Section 4 that a theoretical vertical source can excite a pure Zenneck wave: it can be easily demonstrated [12] that it corresponds to

$$\vec{J} = I_{ds} e^{ik_{Ze}z}\hat{z} \tag{14}$$

Therefore, since the physical realization of an infinite vertical source is impossible, a pure Zenneck wave does not seem to be excitable. Thus, we have to truncate the source. The behavior of the vertical component of the electric field excited by a vertical antenna supplied by the current distribution of (14), when truncated at the height $z = 15\lambda$, is shown in Fig. 8. It can be seen that the total field is not superposed to the bulk waves field anymore, even if, as the distance from the source increases, the total field tends to differs more and more from the Zenneck wave.

As previously, in order to compare the modal approach to the more realistic Norton's one, we synthetize the y-homogeneous current distribution with an array, as depicted in Fig. 5. We have simulated

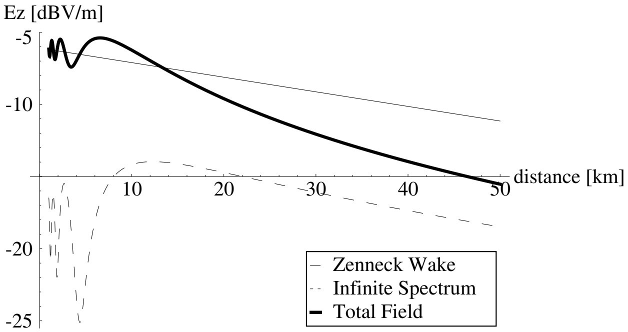

Figure 8. Decomposition of the field excited by a homogeneous current density $\vec{J} = I_{ds} e^{ik_{Ze} z} \hat{z}$ truncated at a height of 15λ, on the sea surface at $f = 10\,\text{MHz}$.

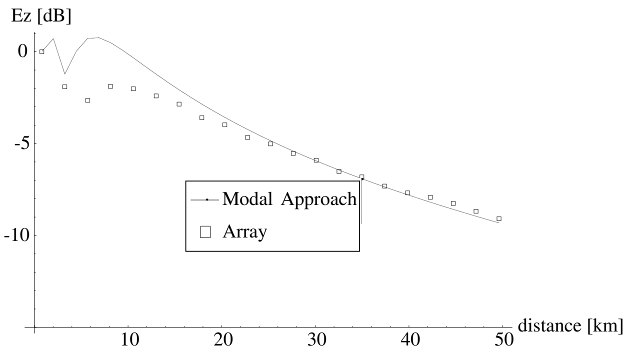

Figure 9. Vertical component of the electric field radiated by the array ($N = 2000$, $\delta y = \lambda/2$), where each antenna is constituted of 21 Hertzian dipoles, and by a current density $\vec{J} = I_{ds} e^{ik_{Ze} z} \hat{z}$ truncated at the height $z = 15\lambda$. The calculations are performed at the interface for $f = 10$ MHz. Fields are normalized to their values at $R = 30\lambda$.

a quasi-infinite array of current lines; each line is constituted by 21 Hertzian dipoles, which synthetize the current distribution of (14). For the nth dipole, the current moment is:

$$I_{ds_n} = I_{ds_0} e^{ik_{Ze} n \delta z}, \qquad n = 0, 1 \ldots, 20 \tag{15}$$

where $\delta z = 15\lambda/20$. In Fig. 9, we have plotted the decay of the vertical component of the electric field excited by this last array and by the y-homogeneous current of Equation (14). Globally, the results are in accordance: some difference is observed in the oscillatory zone comprised between 1 and 10 km, but the two graphs tend to merge as distance is increased. It seems therefore that the vertical current distribution does not need to be continuous and a vertical array can be substituted for it.

The simultaneous investigation of a realistic current density and an optimized surface impedance designed in order to maximize the Zenneck contribution will be the subject of further papers.

6. CONCLUSION

Despite the fact that High Frequency Surface Wave Radars are the sole available tool for maritime surveillance up to the Exclusive Economic Zone limits, they suffer from a lack of directivity of their transmitting antennas. Thus the coverage is not as good as it could be and the signal processing should include ionospheric clutter mitigation. Surface wave is a long-past known phenomenon also used by HF communication systems. Nonetheless, specific surface wave radiating antenna has not yet been developed. We aim to design such a new radiating element for HFSWR applications.

As a first answer to that issue, we have proposed to use the modal approach to isolate the well-known Zenneck wave and fine-tune this primary contribution to surface wave propagation. Thus, we have presented a formal study of the electromagnetic field on sea surface, usually (but not accurately) called surface wave. The modal decomposition allowing to isolate the Zenneck wave, which is the specific propagation mode caused by the interface, has been introduced. Carrying on the analysis based on the modal decomposition, we have shown how the Zenneck wave excitation contributes to the total field at the interface.

More realistic case than infinite sources have been studied. Results obtained in the last section show how the modal approach is valuable to design HFSWR radiating elements. Further studies will also take under consideration the surface impedance of the soil in order to maximize Zenneck contribution.

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