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NEGATIVE PERMITTIVITY MEDIA ABLE TO PROPAGATE A SURFACE WAVE

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Abstract—In the field of High Frequency Surface Wave Radar (HFSWR), this paper deals with a study which determines the electric permittivity and conductivity values that a medium must hold to propagate a sole surface wave at its interface with air. Firstly, we demonstrate clearly the reason why the Zenneck Wave cannot be excited on sea surface. Kistovich decomposition is used for this purpose. Secondly, the reasoning is extended to identify electric permittivity and conductivity values that permit to excite a surface wave on an homogeneous medium. Finally, numerical validation is obtained by comparison with the analytic formulation of the field radiated by a vertical Hertzian dipole as it has been established by Norton.

1. INTRODUCTION

High Frequency Surface Wave Radars (HFSWR) have arisen a great interest as a solution for the surveillance of the Exclusive Economic Zone, a portion of the sea that can be extended by states until 200 nautical miles from the seashore [1]. In fact, this land based and low cost system seems to be the optimum one for constant monitoring [2].

Even if operating systems exist and good performances are achieved, HFSWRs suffer from a major problem: the energy radiated by the transmitting antennas is only for a minor part conveyed at the sea surface. This fact causes, not only an energy loss, but also

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clutter due to the interaction between the electromagnetic field emitted towards the sky and the ionospheric disturbances [3, 4].

We have used Kistovich work [5, 6] to decompose the field at the interface between two dielectric media in a sole surface propagation mode (identified with the Zenneck Wave) and an infinite spectrum of bulk waves. Such a surface wave is characterized by a strong attenuation in the normal direction to the surface of propagation, which concentrates it at the interface.

In this paper we propose a study, in HF frequency range, in order to determine the parameters that a surface must hold to propagate a sole surface propagation mode using Kistovich decomposition [5]. Firstly, we demonstrate clearly the reason why the Zenneck Wave cannot be excited on the sea surface. The use of the saddle-point asymptotic evaluation allows to calculate and to interpret the terms appearing in the modal decomposition. Secondly, this analysis is extended to the general case of an interface between air and a positive electric permittivity medium. Thirdly, Kistovich decomposition is employed to show that only negative electric permittivity materials can propagate a sole surface wave and how they can be used to concentrate the energy at the interface. Finally, the analytical formulations proposed by Norton [7] are used to calculate and plot the field excited by a Hertzian dipole on a negative permittivity surface in order to validate our reasoning.

2. GEOMETRY AND MODAL DECOMPOSITION

In a cartesian coordinate system, with a time harmonic dependency ($e^{-\mathrm{i}\omega t}$), we consider two semi-infinite homogeneous half-spaces separated by an interface parallel to xy plane located at $z = 0$ (see Figure 1). The upper half-space, identified as medium 1, is supposed to be free-space, with a permittivity ε_0 and a permeability μ_0. The electromagnetic fields are characterized by wavenumber $k_0 = \omega/c = \omega\sqrt{\varepsilon_0\mu_0}$, where ω and c are respectively the angular frequency and the speed of light. The lower medium, identified as medium 2, is a homogeneous, lossy medium, of conductivity σ, having relative electric permittivity $\underline{\varepsilon}_r = \varepsilon_{rr} + \mathrm{i}\sigma/(\omega\varepsilon_0)$, such as $|\underline{\varepsilon}_r| \gg 1$, and relative magnetic permeability $\mu_r = 1$.

In this configuration, we define a current density (A/m^2) of the form $\vec{J} = I(z)\delta(x)\hat{e}_z$. The choice of a vertical, y-homogeneous current distribution leads to:

$$E_y = 0; \quad H_x = 0; \quad H_z = 0 \tag{1}$$

The fields in medium 1 can be found by applying at $z = 0$ Leontovich boundary condition [8] for the transverse fields, under the

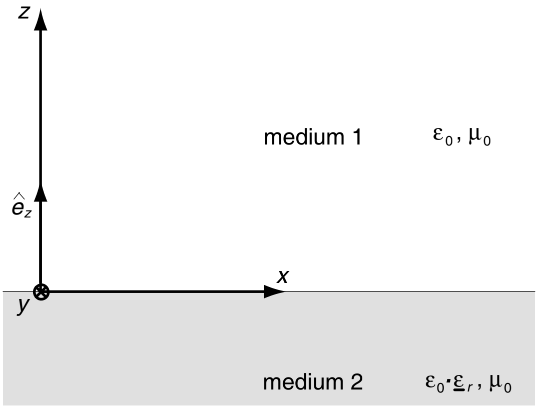

Figure 1. Geometry under consideration.

assumption that $|\underline{\varepsilon}_r| \gg 1$:

$$\vec{E}_t = Z_s \hat{e}_z \times \vec{H}_t; \quad Z_s = \sqrt{\frac{\mu_0}{\varepsilon_0}} \sqrt{\frac{1}{\underline{\varepsilon}_r}} \tag{2}$$

where Z_s is the surface impedance.

The electromagnetic fields can be expressed as the sum of two source-dependent terms. For the magnetic field we have:

$$H_y(x,z) = A\varphi_s(z) e^{\mathrm{i}k_x x} + \int_0^\infty B(p)\varphi_v(z,p) e^{\mathrm{i}\sqrt{k_0^2 - p^2}x} dp \tag{3}$$

where

$$\varphi_s(z) = \sqrt{\frac{2k_z}{\mathrm{i}}} e^{\mathrm{i}k_z z} \tag{4}$$

$$\varphi_v(z,p) = \frac{1}{\sqrt{2\pi}} \sqrt{\frac{p-k_z}{p+k_z}} \left(e^{-\mathrm{i}pz} + \frac{p+k_z}{p-k_z} e^{\mathrm{i}pz} \right) \tag{5}$$

$$k_z = -\omega\varepsilon_0 Z_s \quad k_x = \sqrt{k_0^2 - k_z^2} \tag{6}$$

A and $B(p)$ are determined knowing $I(z)$. Looking at Equation (3), the first term can be identified with a surface wave propagating at the interface and decaying exponentially both in x and z directions. Considering medium 2 as sea water, this surface wave is commonly called the Zenneck wave [9]. The second term represents a continuous spectrum of direct and reflected bulk waves. In the next section, we will discuss the contribution of the surface wave to the total field.

3. INTRINSIC CANCELLATION OF THE SURFACE WAVE ON A POSITIVE ELECTRIC PERMITTIVITY MEDIUM

In [6] it has been observed that, with a current distribution $I(z) = I_0\delta(x)$, Zenneck wave is masked by the bulk waves on the sea surface. The modal decomposition suggested by Kistovich is useful to understand the reason why the Zenneck wave cannot be observed.

Starting from this current distribution, $I(z) = \delta(z)$ (with $I_0 = 1\,\mathrm{A}$), at $z = 0$ we obtain:

$$H_s(x) = -\mathrm{i}k_z e^{\mathrm{i}k_x x} \tag{7}$$

$$H_{bulk}(x) = \frac{1}{\pi}\int\limits_0^\infty \frac{p^2 e^{\mathrm{i}\sqrt{k_0^2-p^2}x}}{p^2-k_z^2}dp \tag{8}$$

where H_s and H_{bulk} are the terms of H_y due to the surface wave and the bulk waves respectively. The total magnetic field is therefore:

$$H_y(x,0) = H_s(x) + H_{bulk}(x) \tag{9}$$

Since Equation (8) cannot be evaluated in closed form, we perform its saddle-point asymptotic evaluation [10, 11]. In order to correctly calculate the integral, we must consider the steepest descent path (SDP) to include any pole residue. The SDP is expressed as:

$$p = p_r + \mathrm{i}p_i, \quad p_i = -\frac{k_0 p_r}{\sqrt{k_0^2+p_r^2}}, \quad 0 < p_r < \infty \tag{10}$$

Knowing the new integration path, it is necessary to discuss the locus of the poles of Equation (8): in particular, the pole $p_0 = -k_z$, which lies in the fourth quadrant of the complex plane, is surrounded by the integration path if medium 2 has the same properties as those of sea water (typically, $\varepsilon_{rr} = 80$ and $\sigma = 5\,\mathrm{S/m}$). The influence of such a pole is crucial since the term due to its residue is $\mathrm{i}k_z e^{\mathrm{i}k_x x}$.

Therefore, the bulk wave contribution is:

$$H_{bulk}(x) = \frac{1}{\pi}\int\limits_{SDP} \frac{p^2 e^{\mathrm{i}\sqrt{k_0^2-p^2}x}}{p^2-k_z^2}dp + \mathrm{i}k_z e^{\mathrm{i}k_x x} \tag{11}$$

Considering Equations (7), (9) and (11), it appears that the surface wave is canceled by the last term of the bulk wave expression, due to the residue of the pole. This is the reason why the Zenneck wave on the surface of the sea does not emerge from the total field.

It is possible in a similar manner to show that the surface wave is always masked for every medium having $\varepsilon_{rr} > 0$.

In order to discuss about the influence of ε_{rr} and σ on the location of p_0 with respect to the integration contour, we have plotted in Figure 2(a) the pole locus for few positive values of ε_{rr}, choosing the appropriate values of σ to not violate the condition $|\underline{\varepsilon}_r| \gg 1$. The steepest descent path is drawn with dotted line. The iso-conductivity curves are those starting in the upper left corner, in a zone corresponding to high values of electric permittivity and turning clockwise as ε_{rr} decreases. Iso-permittivity curves are those turning anti-clockwise from the upper left corner, thus approaching the real axis by decreasing values of conductivity σ. It can be noticed that for $\varepsilon_{rr} > 0$ (whatever the value of conductivity is) the pole is always located between the SDP and the positive real axis, and then surrounded by the integration path. Thus, the surface wave on a medium having $\varepsilon_{rr} > 0$ is always canceled by the bulk wave contribution.

4. SURFACE WAVE ON A NEGATIVE ELECTRIC PERMITTIVITY MEDIUM

As it can be seen Figure 2(b), if $\varepsilon_{rr} < 0$, the pole $p_0 = -k_z$ is not surrounded by the integration path. So, a way to successfully excite a surface wave may be to choose a negative electric permittivity material as medium 2 [12]. Then, with such a medium, the contribution of the surface wave could be significantly stronger than that of the

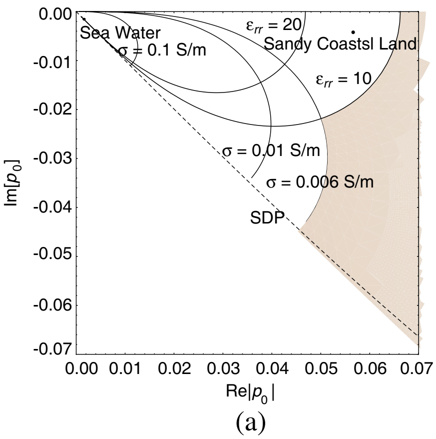

Figure 2. Pole loci at $f = 10\,\mathrm{MHz}$. The brown zone is forbidden since it violates the condition $|\underline{\varepsilon}_r| \gg 1$ at this frequency. (a) $\varepsilon_{rr} > 0$. (b) $\varepsilon_{rr} < 0$.

bulk wave, at least at short range. Therefore, we have to study the influence of the electric properties of medium 2 on the surface wave strength in order to maximize its magnitude at $x = 0$ and minimize its decrease rate in x-direction. In accordance with Equation (7), we need to maximize $|k_z|$ and minimize the imaginary part of k_x, $\mathrm{Im}[k_x]$ under the constraint $|\underline{\varepsilon}_r| \geq 10$ (which is chosen as the minimum and practical requirement in order to fulfill $|\underline{\varepsilon}_r| \gg 1$). Minimizing $\mathrm{Im}[k_x]$, is equivalent to suppose that medium 2 is lossless. Maximizing $|k_z|$ under the constraints $|\underline{\varepsilon}_r| \geq 10$ and $\sigma = 0$, leads to choose $|\underline{\varepsilon}_r| = -\varepsilon_{rr} = 10$ and then $k_z = \mathrm{i}k_0\sqrt{\frac{1}{10}}$.

Nevertheless, we want to extend our solution to lossy dielectric materials, since they are more realistic. Then, setting $\varepsilon_{rr} = -10$, we have plotted, in Figure 3, $|k_z|$ and $\mathrm{Im}[k_x]$ for various values of the electric conductivity σ. It can be noticed that $|k_z|$ is monotonically decreasing with σ. The curve $\mathrm{Im}[k_x]$ presents a maximum. As a consequence, two different values of σ can give rise to the same attenuation in the x-direction. Figure 4 shows the total field and its two contributions at $z = 0$. It is drawn as a function of distance x for four media having $\varepsilon_{rr} = -10$ and values of σ corresponding to the four points indicated in Figure 3.

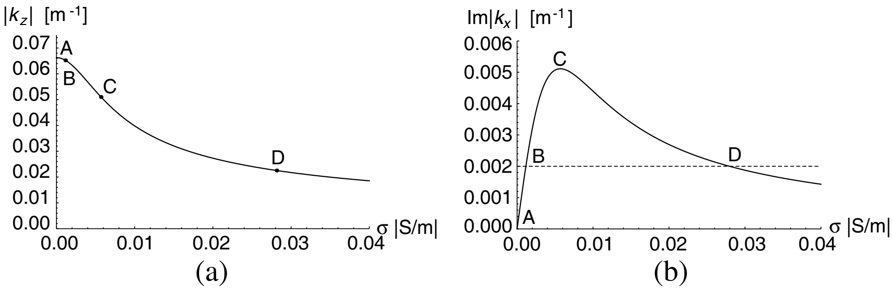

Figure 3. $|k_z|$ and $\mathrm{Im}[k_x]$ as function of σ for $\varepsilon_{rr} = -10$ and $f = 10\,\mathrm{MHz}$.

The behavior of the complex wave is in accordance with what was expected, while the behavior of the bulk waves field is clarified. The choice of smaller values of electric conductivity (points A and B) than those corresponding to the maximum value of $\mathrm{Im}[k_x]$ (point C), offers the double advantage of an intense, slowly decaying surface wave and a weak bulk waves field.

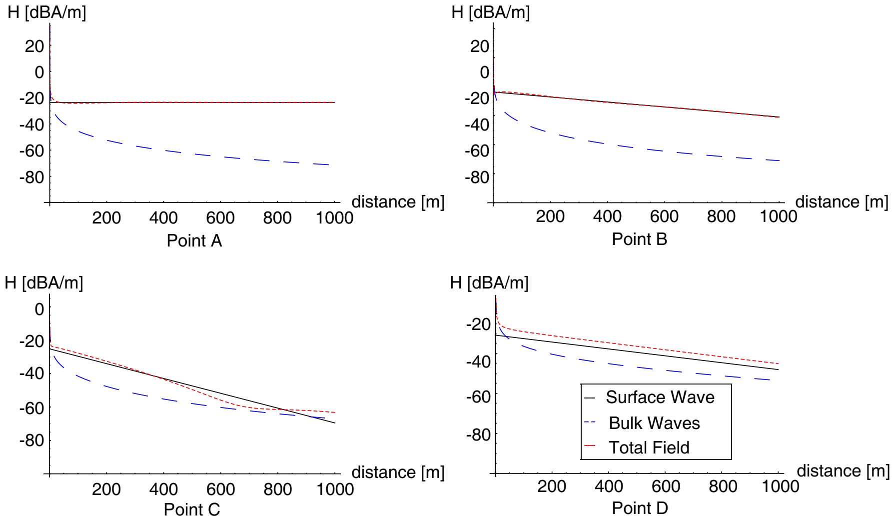

Figure 4. Magnitude of the magnetic fields issued from the modal decomposition for $\varepsilon_{rr} = -10$ and various values of the conductivity σ (corresponding to points A to D), at $f = 10\,\text{MHz}$.

5. RESULTS

We extend our analysis of the field propagating above negative electric permittivity media by considering a vertical Hertzian dipole (located at the origin of the coordinate system), which is more realistic than the y-infinite vertical source. The polar representation of the radiated electric field, corresponding to points B, C and D of the previous section, are shown at two different distances d_1 and d_2 from the source in Figures 5(a) and (b) respectively. The case of point A is not presented because of its similar behavior to the case of point B. It can be noticed that, at a short distance from the source, the magnitude of the field on the surface decreases from point B to point D, in accordance with the dependency of $|k_z|$ on σ. In the same way, at a larger distance, the attenuation of the surface wave for point C is higher than that of points B and D, in accordance with the dependency of $\text{Im}[k_x]$ on σ. At very low elevation angles (few degrees), point B is still the best configuration: the surface wave is maximum and the space wave is weakly excited. Moreover, at high elevation angles, field levels for the three points are equivalent: the surface wave has completely vanished and the bulk waves do not seem to be influenced by the surface characteristics.

Finally, we compare the best configuration we have studied (i.e., point B) with two real homogeneous soils like sea water ($\varepsilon_{rr} = 80$, $\sigma = 5\,\mathrm{S/m}$) and sandy coastal land ($\varepsilon_{rr} = 10$, $\sigma = 10^{-3}\,\mathrm{S/m}$). Looking at Figure 6, it is clearly confirmed that a negative electric permittivity medium enhances the field radiated close to its surface and limits the space field at elevation angles larger than approximatively 4°.

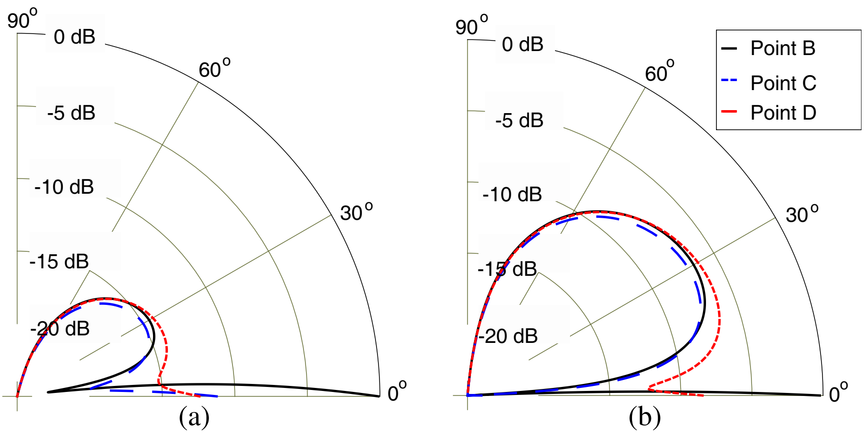

Figure 5. Polar representation, at two given distances from the source, of the normalized magnitude of the electric field radiated by a vertical Hertzian dipole at $f = 10\,\mathrm{MHz}$. (a) Distance $d_1 = 10\lambda$. (b) Distance $d_2 = 30\lambda$.

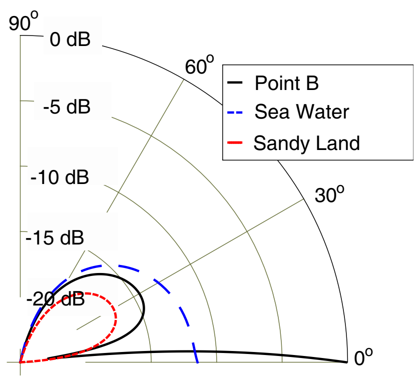

Figure 6. Polar representation, at 10λ from the source, of the normalized magnitude of the electric field radiated by a vertical Hertzian dipole at $f = 10\,\mathrm{MHz}$ over three different media.

6. CONCLUSION

In this paper we have proposed a theoretical approach to study the existence of a surface wave at the plane interface between air and a dielectric material. Using Kistovich formalism, we have demonstrated that the surface wave cannot be excited on the sea surface nor on any positive electric permittivity medium. This is due to the fact that the complex pole in bulk waves expression is surrounded by the integration path. To encompass this limitation, a shifting of the pole outside the integration path is necessary.

Thereafter, the successfully excitation of the surface wave is possible only if the relative electric permittivity ε_{rr} of the medium is negative. An analysis of the wave numbers involved in the determination of the surface wave has allowed us to define the electric characteristics of a medium able to concentrate the field close to the surface. The field of a Hertzian dipole above negative electric permittivity media has been calculated using Norton's equations to extend the approach to finite sources. Those results are sufficiently conclusive to envisage further studies to physically realize a surface able to support a surface wave at HF frequencies. Nevertheless, for obvious and practical reasons, experimental validation has to be planned on a L band prototype while thoroughly respecting the electromagnetic similitude principle.

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