Prediction of HF wave propagation for "over the horizon" radar application

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Abstract— **This paper deals with the problem of HF surface wave radar. The goal is to integrate in a unique tool the antenna radiation and the propagation calculations in order to make the analysis consistent. Only the antenna problem is presented here. However the way the propagation problem will be further considered is presented. Cross check of the tool validity and robustness were insured by developing concurrently several techniques, mixing measurements and theoretical techniques.**

I. Introduction

This paper addresses the problem of the surface wave radar[1]. This kind of radar, usually operating in the HF band, has a growing interest in many applications, in particular for the survey of the coastal maritime sectors. Contrary to the sky wave, also radiated by a HF radar, the surface or ground wave decays as the square root of the distance to the source. As a result, and with a reasonable transmitted power, the signal can be propagated over hundreds of kilometers. Such a propagation mode complements the sky wave pattern of HF radars which shows a blind zone up to the first ionosphere reflection distance.

To fully characterize the problem, both the antenna characterization and matching, the near field pattern and the propagation problem have been addressed. The antenna current distribution has been calculated using the integral equation technique [1]. Two numerical approaches to properly take the interface into account were developed concurrently. One advantage of the technique is to isolate the ground wave contribution and estimate the related radiated power. Once the current distribution is found, the near field and the far field pattern (including the ground wave contribution) can be obtained. In addition as a cross check validation, a finite difference time domain technique was developed concurrently.

[1] This study has been carried out in the frame of the PROPHETE project under funding of the French Research National Agency (ANR)

Another approach to the antenna problem consists in using a near field - far field transformation using measurements. An HF antenna is usually located above the ground and may reach dimensions up to 15 m height. As the ground interface is part of the radiating structure, this puts some constraints on the measurement setup. A specific equipment is being studied for this purpose. The measurements will be performed using a 3D electric probe moved over a virtual cylindrical surface containing the antenna. The location of the sensor will be simultaneously recorded at each measurement point. The corresponding virtual magnetic currents distribution will allow to calculate the field radiated at any point in the outer space. Those measurements will be tested firstly on a 1 GHz scale model and then applied to the actual HF antenna.

The ground wave propagation over an irregular, inhomogeneous terrain can be derived using the parabolic equation. The problem is an initial value problem with the ground wave field contribution acting as a driver, as the sky wave has no contribution in the interface plane. Two techniques were developed concurrently. The first one uses the classical split step technique while the second uses a finite difference scheme. Both of them allow to include discontinuities in the electrical ground constants. In particular, the Millington effect, consisting in the recovery of the field after crossing a land with a higher conductivity, has been verified.

As regards the terrain generation, specially for the sea surface, a rough surface model based on the fractal Diamond-Square so-called algorithm has been implemented. The sea surface is generated, based on a Pierson - Moskowitz spectral density model. It has been shown that the Doppler spectrum of the sea can be observed in the transmitted signal.

The points related to the antenna problem are detailed in the following sections.

II. THE ANTENNA PROBLEM

As derived by Michalski [2], there are three different ways to write the Lorentz gauge relationship in order to meet the boundary conditions on the interface. Although equivalent from a theoretical point of view, his formulation C is the most convenient as regards its numerical implementation. This formulation has been used in the present development. With respect to the Electric Field Integral Equation (EFIE), the new equation, named Mixed Potential Integral Equation (MPIE), includes additional terms to take the Green's function modification into account.

The MPIE integral terms all involve the so-called Sommerfeld integrals. Two techniques can be used for their numerical evaluation, either the Phase Stationary Technique (PST) or the Complex Image Technique (CIT). These two techniques have been developed concurrently.

The phase stationary technique is the classical one. It consists in finding the steepest descent contour in the k_ρ complex plane. This contour has branch cuts as the function to integrate has branch points. The complex image technique [3-4] takes benefit from the easiness to consider images in a method of moments procedure. The aim of the calculation consists in representing the MPIE integral terms by a sum of terms, each of them being amenable to a Weyl like integral term. The integration is performed in the k_z complex plane. The integration contour is linear in this plane. Figure 1 shows a comparison of the E_z contribution of a vertical Electric Dipole (VED) obtained with the two techniques. The agreement is excellent.

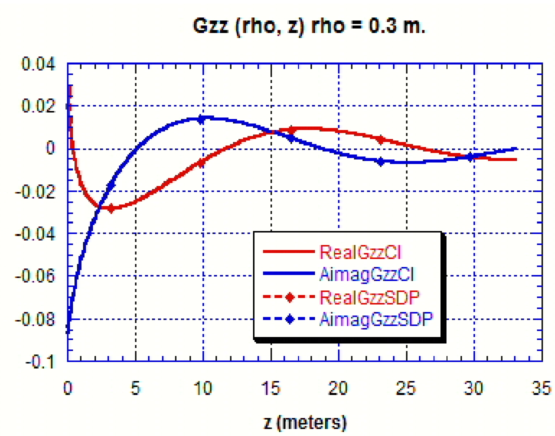


Figure 1 : Comparison of the electric field vertical component contributions due to a vertical dipole obtained with the phase stationary and the complex image technique

In addition to the contour contribution, the result shall integrate the poles contribution. The corresponding terms is the surface wave radiated by the HF antenna.

Again, the comparison between the two techniques has been performed. For the phase stationary technique, none of the poles are located inside the integration contour. However they are very close to it. As a result in order to make the calculation numerically tractable, it is necessary to remove their contribution in the integrand to get a regular function. It is subsequently reintroduced and calculated separately. This is the so-called modified saddle point calculation technique. For the complex image technique, all poles of the function should be included irrespective to their sign. They are considered by pairs. The comparison is shown in figure 2.

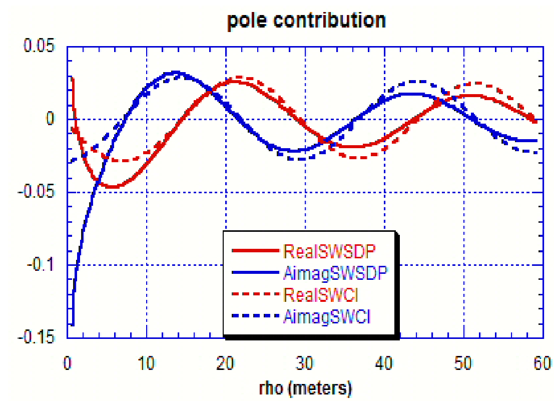


Figure 2 : Comparison of the electric field vertical component contributions due to the pole contribution for a vertical dipole obtained with the phase stationary and the complex image technique

<u>Summary</u>

For its implementation in a method of moments code, the Sommerfeld integral terms should give accurate results whatever the problem parameters such as the frequency, the distances and the electrical medium parameters are. To this respect, the complex image might be the most convenient technique, as accurate developments can be used for the critical values in the integration complex plane, namely when k_ρ and ρ tend to zero.

For the surface wave contribution, an analytical solution involving the error function, can be derived using the modified saddle point technique.

III. NEAR-FIELD TO FAR-FIELD (NF/FF) TRANSFORMATION IN THE HF BAND

The proposed method is based on a source identification assuming that the antenna under test (AUT) can be replaced by a set of equivalent dipoles radiating the same far-field as the AUT. This approach, based on the equivalence principle, has been already described by several authors [5, 6]. Nevertheless, the innovative point brought by this new method is the use, as dipole's radiation functions, of the analytic formulations developed by Norton [7] and extended by Bannister [8] to the very near field zone. These formulations comprise the sky wave, which is the sum of the direct and reflected waves, as well as the surface wave contribution of the electromagnetic field radiated by each elementary dipole.

A. Description of the method

Consider an AUT located at the plane horizontal interface between air and real ground. In a cylindrical coordinate system (ρ, φ, z), the components of the electromagnetic field are measured in the near-field zone (in order to measure the surface wave) on a virtual surface S_M surrounding the AUT. For convenience, we will first assume that S_M is a cylindrical surface, of radius r_{SM} and height h_{SM}, centered on the AUT represented in Fig. 3. The surface S_M is meshed with a maximum spatial sampling step equal to $\lambda/2$, where λ is the wavelength is free space. The number of measured points is N_M. Consider now a second virtual surface S_D, included inside the surface S_M. Also, for convenience, the surface S_D is supposed to be a cylinder of radius r_{SD} and height h_{SD}, centered on the AUT (see Fig. 3). It is also meshed with a maximum spatial sampling step equal to $\lambda/2$. The number of mesh points is N_D. At each point, three elementary electric dipoles are arranged in order to form an orthogonal basis aligned with the cylindrical basis vectors.

The method states that, at each point of the surface S_M, the electromagnetic field, is equal to the sum of all the contributions coming from each of the $3N_D$ dipoles spread on the surface S_D. This leads to the following matrix equations:

$$\boldsymbol{E_{SM}} = \boldsymbol{D_E} . \boldsymbol{P_{SD}} \quad (1)$$

$$\boldsymbol{H_{SM}} = \boldsymbol{D_H} . \boldsymbol{P_{SD}} \quad (2)$$

Where $\boldsymbol{E_{SM}}$ and $\boldsymbol{H_{SM}}$ are respectively the electric and magnetic vectors of size $3N_M$, measured at each point on the surface S_M. $\boldsymbol{D_E}$ and $\boldsymbol{D_H}$ are respectively the electric and magnetic radiation matrices (issued from the Norton/Bannister formulations), of size $3N_M \, x \, 3N_D$, concerning the $3N_D$ electric (horizontal and vertical) dipoles located at each point of the surface S_D. $\boldsymbol{P_{SD}}$ is the unknown vector, of size $3N_D$, containing the electric moments of the previous dipoles.

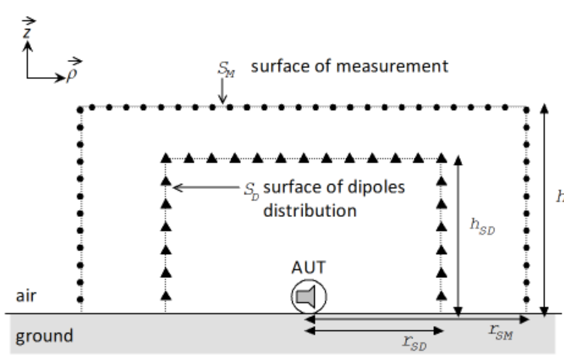


Figure 3: Geometry corresponding to the method.

Equations (1) and (2) can be written in the following reduced form (3) and solved by inversion of the matrix $\boldsymbol{D_{EH}}$ in order to determine the vector $\boldsymbol{P_{SD}}$.

$$(\boldsymbol{EH})_{SM} = \boldsymbol{D_{EH}} . \boldsymbol{P_{SD}} \quad (3)$$

The accuracy of the inversion is influenced by the number of dipoles contributing to the radiation. Particularly, it is necessary to unselect the dipoles which have a non-significant contribution to the total field. As a consequence, this inversion is carried out by applying a singular value decomposition (SVD) to the matrix $\boldsymbol{D_{EH}}$ associated with a threshold power criterion. This criterion represents the total power radiated by the AUT, in the near-field zone, and is calculated from the measurement of the electromagnetic field on the surface S_M. Then the singular values matrix is scanned by decreasing order until the corresponding calculated power reaches this power criterion. Once the vector $\boldsymbol{P_{SD}}$ is determined, the electric far field can be easily computed from the direct linear system (1).

B. Approximation of the magnetic field

The input data of the NF/FF transformation require the measurement of both electric and magnetic fields to compute the power criterion and apply the SVD. Nevertheless, in order to have a less expensive and a less cumbersome device, we have decided to use only an electric field probe. By considering the radiated wave as a plane one, we can estimate the spherical component $\boldsymbol{H_\varphi}'$ of the magnetic field from the measurement of the spherical component $\boldsymbol{E_\theta}$ of the electric field using

$$\boldsymbol{H_\varphi}' = \boldsymbol{E_\theta}/\eta \quad (4)$$

where η is the free space wave impedance.

The AUT represented in Fig. 4 is a biconical antenna working at 10 MHz ($\lambda = 30$ m), with a 3 m radius and a 7 m height, placed over a dry soil which parameters are $\varepsilon_r = 15$ and $\sigma = 0.005$ S.m^{-1}. The antenna has a wired ground plan; each wire is 19 m long and the dry soil is a cube of $4\lambda \, x \, 4\lambda$ x 2λ. The simulation was performed with the TLM solver of CST MWS.

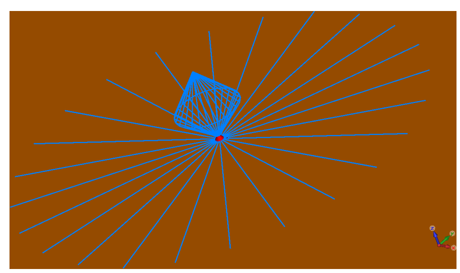


Figure 4: Biconical antenna over a dry soil.

The cylindrical components $\boldsymbol{E_z}$ and $\boldsymbol{H_\varphi}$ of the electric and magnetic fields respectively are computed on the measurement surface described in Fig. 3. This surface is a cylinder whose radius is equal to λ; the top and the bottom of the cylinder are not considered.

To apply the power criterion, we are only interested in the computation of the radial power $\boldsymbol{S_\rho}$, computed from $\boldsymbol{E_z}$ and $\boldsymbol{H_\varphi}$. The component $\boldsymbol{H_\varphi}'$ is the approximated magnetic field given by equation (4) and $\boldsymbol{S_\rho'}$ the corresponding approximated radial power.

The total active power radiated through the cylindrical measurement surface can now be calculated in the two configurations (and are called P_{rad} and P_{rad}' respectively).

The results are summarized in Tab. I. The difference between the two powers is equal to 0.9 %. That means that our plane wave approximation is good enough to unselect the dipoles which are not relevant to the total field contribution.

TABLE I. COMPARISON OF THE RADIAL POWERS RADIATED THROUGH THE CYLINDER.

P_{rad} (mW)	P_{rad}' (mW)	Difference (%)
332	329	0.9

IV. OBTAINED RESULTS

A. Icare (MoM) results

The case considered is a typical biconical antenna of 7 meters height placed on the ground (relative dielectric constant 15 and conductivity 0.05 S / m). The calculation provides the VSWR, the currents and the fields (near field, far field and ground wave). The antenna current distribution is shown in Fig. 5.

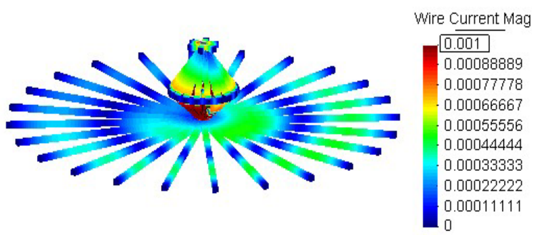
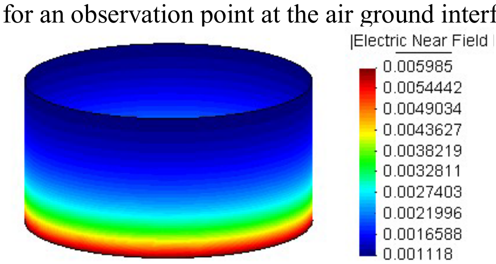


Figure 5 : Currents distribution on the HF antenna

Figure 6 depicts the near field pattern on a cylindrical surface containing the antenna. The major contribution comes from the ground wave. It decreases very rapidly with the altitude and as the inverse of the square root of the radial distance to the antenna for an observation point at the air ground interface.



Electric Field Magnitude (V / m)

Figure 6 : The near field radiated by the antenna on a cylindrical surface of radius 100 meters with the antenna at its base centre.

B. Future measurement

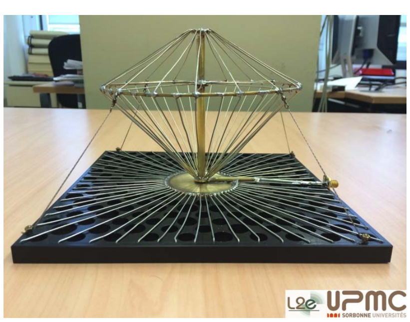


Fig. 7. 1 GHz antenna scale model (MC 10-25).

The 1 Ghz scale model of the antenna is shown on Figure 7. The field probe EFS-105 [9] will be used for the measurements

V. CONCLUSION

Two approaches aiming to estimate the field radiated by an HF antenna were presented. The first one is a theoretical approach. Comparisons were made between the phase stationary and the complex image techniques. These techniques were checked over a wide range of parameters. A special interest was devoted to the ground wave calculation for which an analytical expression was derived.

The second approach uses a near field – far field transformation with measurements data as an input. A dedicated measurement setup was developed in this respect. An original technique was developed for dissemination of the dipoles allowing to rebuild the far field.

Comparisons between the results provided by these two approaches were fully satisfactory.

The ground wave contribution is the source term of the propagation problem. It is calculated at the vicinity of the antenna. The propagation problem is solved using a 2D algorithm in agreement consequently with the field radial dependency. The electrical ground parameters and height profile can take any value along the propagation axis. Again, two techniques were developed for the propagation problem, one based on a finite difference calculation and the other one on a Fourier split step algorithm.

The final tool allows considering an arbitrary HF antenna and environment. The calculation time is small enough to perform sensitivity analysis regarding the problem parameters, in particular the terrain profile and characteristics.

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