Electromagnetic Virtual Tools for the Visualization of Antenna Radiations and Radiowave Propagation

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***Abstract*— Understanding electromagnetics (EM) is essential for EMC Engineers. In addition to learning physics behind mathematics, i.e., Maxwell equations, using virtual tools with the aim of visualization of antenna system radiations, EM scattering and diffraction, as well as radiowave propagation are also essential. Here, simple MATLAB-based virtual tools ArrayGUI and SSPE_GUI are introduced for the visualization of radiation characteristics of basic antennas and their arrays and for the simulation of radiowave propagation.**

Keywords—Engineering education, teaching electromagnetics, simulation, visualization, virtual tools, MATLAB, Graphical User Interface (GUI), planar arrays, element pattern, array factor, antenna radiation pattern, radiowave propagation, free space model, two-ray model, terrain modeling, split step parabolic equation (SSPE) method

I. Introduction

Experimentation via real and virtual laboratories play an important role in engineering education. Electromagnetic (EM) curricula should therefore aim to establish an intelligent balance between real and virtual experimentations [1,2]. Moreover, teaching/training electromagnetics to the computer-weaned, internet oriented next generations has become a hot topic in many conferences and congress.

Triggered by this philosophy, several MATLAB-based user-friendly electromagnetic virtual tools have been developed and introduced to the use of the readers [3-11]. These simulation packages can increase teaching efficiency in electromagnetic courses, such as “Antennas and Propagation”, “Electromagnetic Field Theory”, “Electromagnetic Wave Theory”, Wireless Communication”, “Engineering Electromagnetics”, “Fundamentals of EMC”, etc.

The packages RAY_GUI and HYBRID_GUI [3] are designed to investigate individual rays and modes, and their collective field contributions inside a two-dimensional (2D) non-penetrable parallel plate waveguide. A Multi-purpose FDTD-based EM Virtual Tool was introduced in [4]. The MATLAB-based visualization package ANTEN_GUI [5] investigates beam forming and beam steering capabilities and radiation characteristics of 1D and 2D planar arrays of isotropic radiators. SSPEGUI [6] is another virtual tool designed to visualize wave propagation over user-specified, non-flat terrains and through non-homogenous atmosphere. Another MATLAB-based simulation package TDRMeter [7] enables the user to investigate pulse propagation along a transmission line and to simulate different types of terminations and/or reflections from various discontinuities. The visualization package ComplexGUI [8] was developed to investigate elementary multi-valued complex functions, their Riemann surfaces, branch points, branch cuts and their mappings. The virtual tool BESSEL_GUI [9] describes high frequency methods such as stationary phase method, steepest descent path evaluations, and uniform asymptotics and their use in evaluating different types of Bessel integrals. Both packages ComplexGUI and BESSEL_GUI can be used in graduate EM lectures to discuss complex integration and contour deformation techniques in detail. Besides the above-mentioned MATLAB-based packages, DOGUS_FFT [10] is a LABVIEW-based virtual tool prepared to calculate Fourier transforms numerically and to visualize phenomena such as scalloping loss, spectral leakage, and aliasing. Most of these tools were discussed as web-based teaching/training tool in [11].

The ArrayGUI introduced in Section 2 of this paper is an improved version of the above-mentioned virtual tool ANTEN_GUI [5]. ANTEN_GUI was capable of plotting radiation patterns of arrays of isotropic radiators, which corresponds to the array factor of arrays of different kind of antennas. ArrayGUI can be used to plot element patterns of individual radiating elements such as the hypothetical electric / magnetic dipoles and dipoles with standing wave / travelling wave current distributions. It is also capable of plotting array factors and total radiation patterns of arrays of these radiating elements. ArrayGUI allows not only uniform excitations but also binomial excitations of the dipoles.

Section 3 discusses how virtual tools can be used to visualize radiowave propagation. First the most primitive models, the free space model and the two-ray model are given and compared with each other according to their validity regions. A small MATLAB script is included which plots the received power versus distance graphs computed using the Friis formula and the two-ray model. Finally, the propagation over non-flat terrains and through in-homogenous atmosphere is investigated using the virtual tool SSPE_GUI. Section 4 contains the concluding remarks.

II. VISUALISATION OF ANTENNAS AND THEIR ARRAYS VIA THE ARRAYGUI PACKAGE

The user interface of the package ArrayGUI is displayed in Fig. 1. The user may choose from a popup menu arbitrary, linear, planar or circular array of radiating elements located on the x-y plane. Once the operating frequency, the number of the elements, the interelement distances of the linear / planar array or the radius of the circular array are specified, pressing the "Locate Radiators" button displays the radiators on the graph. If the array type is chosen as arbitrary, the user locates every radiator one by one by left clicking the mouse. The coordinates of the radiators are shown at the list box just below the "Locate Radiators" button.

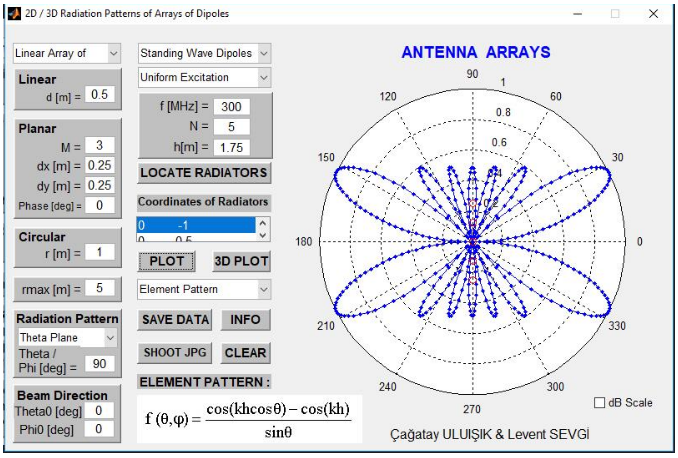

Fig. 1. The user interface of ArrayGUI. The vertical radiation pattern of a single standing wave dipole (f=300 MHz, h=1.75 m).

As an improvement to the ANTEN_GUI package this tool also allows the user to choose the type of the radiating element as an electric dipole, magnetic dipole, standing wave dipole or travelling wave dipole, all of which are z-directed. The element pattern of a z-directed electric or magnetic dipole is determined by the formula $f(\theta) = sin(\theta)$. The element pattern of a standing wave dipole is given by $f(\theta) = \frac{cos(khcos(\theta)) - cos(kh)}{sin(\theta)}$ and the element pattern of a traveling wave dipole is specified by $f(\theta) = \frac{sin[kh(cos\theta - 1)]}{cos(\theta) - 1} sin(\theta)$, where k is the wave number and h is the height of the dipole. Once the type of the radiating element is chosen the formula of the element pattern is displayed at the bottom.

After locating the radiators two-dimensional or three-dimensional radiation patterns can be displayed by pressing the "Plot" or "3D Plot" buttons. The two-dimensional radiation plane to be displayed is specified via a popup menu as Theta Plane or Phi Plane. If the Theta Plane is selected the vertical radiation pattern at a fixed user specified phi angle is displayed and if the Phi Plane is selected the horizontal radiation pattern at a fixed user specified theta angle is displayed. Using another popup menu, the user may choose to plot either the element pattern or the array factor or the total radiation pattern, which is obtained by pattern multiplication of the element pattern and the array factor.

Fig. 1 shows a linear array consisting of five standing wave dipoles of height h=1.75 m with interelement spacings d=0.5 m. The element pattern of this array is displayed at a vertical plane in Fig 1. The three-dimensional total radiation pattern is displayed in Fig. 2.

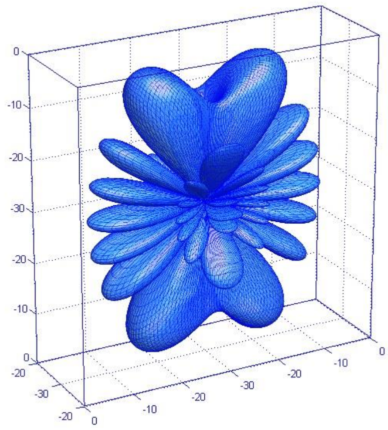

Fig. 2. The three-dimensional radiation pattern of a linear array consisting five standing wave dipoles (f=300 MHz, d=0.5m, h=1.75 m).

At the ANTEN_GUI package the radiators could only be excited uniformly. However, ArrayGUI also allows to excite the elements binomially.

The array factor of a linear array consisting of seven uniformly excited traveling wave dipoles with interelement spacings d=1 m is displayed in horizontal plane in Fig. 3. Then the seven dipoles of the same array are excited instead of uniformly, binomially with amplitudes 1V, 6V, 15V, 20V, 15V, 6V and 1V, respectively. The horizontal array factor of this binomially excited array is shown in Fig. 4. By selecting a Check Box at the lower right corner of the graph, array factors shown in Fig. 3 and Fig. 4 are plotted in dB scale. Comparing these array factors for the uniform and binomial excitations, it is obvious that due to the tapering effect of the binomial excitation, the number of side lobes is decreased drastically.

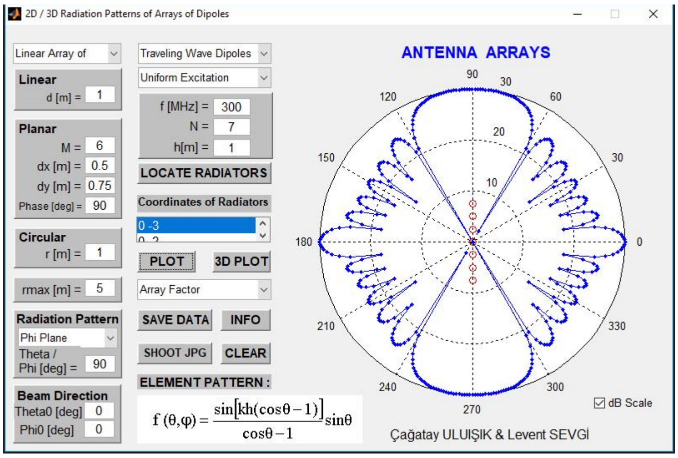

Fig. 3. The array factor of a linear array in a horizontal plane consisting seven elements excited uniformly (f=300 MHz, d=1 m).

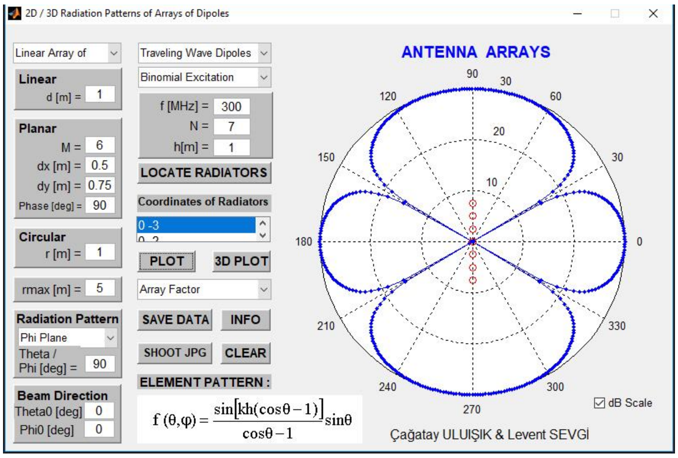

Fig. 4. The array factor of a linear array in a horizontal plane consisting seven elements excited binomially (f=300 MHz, d=1 m).

The ArrayGUI package can be used in "Antennas and Propagation" lectures effectively. First, by selecting the number of elements of the array as N=1 and plotting its array factor, one can observe that a point source radiates isotropically in all directions over a sphere centered on the source and any plane cut will be a circle.

By plotting the element pattern of a z-directed electric / magnetic dipole, one can easily visualize that the radiation pattern of these elements will be donut-shaped and its horizontal radiation pattern will be a circle while its vertical radiation pattern will include only two beams at θ=90° and θ=270°.

If the element type is selected as a standing wave resonant dipole and its vertical element pattern is plotted, a student can check that for the dipole heights much smaller than the wavelength (h<<λ), the radiation will exactly be like the one of an electric dipole. He can also observe that there will be more than two lobes only for $h>0.5\lambda$ and with increasing h/λ ratio the number of side lobes will increase and that the beamwidth will decrease.

If the array type is chosen as "*Planar*" and the number of the elements in the array in y and x-coordinates are chosen as for example N=1 and M=5, than a linear array will be formed and it will be possible to phase the elements linearly with desired interelement phasings. A student can verify that for phase angles α=0°, the horizontal radiation pattern will have a main beam maximum in a direction normal to the plane, which corresponds to the broadside case. If the phase angle will be selected as $\alpha=\pm kd_x$, than the main beam will be in the plane containing the array, which corresponds to the endfire case. Here k is the wave number defined by $k = 2\pi/\lambda$ and d_x is the interelement spacing in x-direction. If the interelement spacing is chosen as d_x=0.5 m, and the frequency as f=300 MHz, than the phase angle α=180° will result in a radiation in the endfire direction.

A student can also observe that both the beamwidth between first nulls and half power (3 dB) beamwidth of an uniformly excited linear array decrease if the frequency f, the number of elements N or the interelement spacing d is increased. By carefully increasing the parameters f , N and d, a student may realize that the beamwidth is proportional to the term $1/(fNd)$ for the broadside case and for the endfire case it is proportional to the term $1/\sqrt{fNd}$ provided that the length of the array is much greater then the wavelength, i.e. Nd >>λ.

III. Visualisation of Radiowave Propagation

The propagation section of an "Antennas and Propagation" course should begin with the free space radio propagation model which is the most primitive model. At this model the transmitter and the receiver are located in free space with no obstacles between them and no ground below them. According to the Friis formula the received power P_r can be calculated in terms of the transmitted power P_t, transmitter and receiver antenna gains G_t and G_r, the wavelength λ and the distance d between the transmitter and the receiver as

$$P_r = \frac{P_t G_t G_r \lambda^2}{(4\pi d)^2}. \quad (1)$$

After the free space model, a lecturer may go on with the two-ray ground reflection model, where the transmitter and the receiver are in line of sight (LOS) and a flat perfect electric conductor (PEC) ground lies under them. The received signal has two components, the LOS component and the single ground reflected wave. According to the two-ray model the received power P_r can be calculated as

$$P_r = \frac{P_t G_t G_r \lambda^2}{(4\pi d)^2}\left|1 - e^{-j2\pi\Delta s/\lambda}\right|^2 \quad (2)$$

where Δs is the path difference between the LOS wave and the ground reflected wave which equals to

$$\Delta s = \sqrt{(h_t + h_r)^2 + d^2} - \sqrt{(h_t - h_r)^2 + d^2} \quad (3)$$

where h_t and h_r are the heights of the transmitter and receiver antennas, respectively. If the distance d is much greater than a critical distance d_c defined by $d_c = 4\pi h_t h_r/\lambda$, then the received power can be approximated as,

$$P_r = \frac{P_t G_t G_r h_t^2 h_r^2}{d^4}. \quad (4)$$

A useful MATLAB script is listed in Table 1, which plots the received power versus distance graphs computed using the Friis formula (1) and the two-ray model without (2) and with (4) approximations. The output graph of this script is shown in Fig. 5. If the distance d is smaller than the transmitting antenna height, the LOS wave and reflected wave are added constructively to yield greater received power. As distance d increases up to the critical distance, both waves add up constructively and destructively, resulting in an oscillatory region which can be observed in Fig. 5. For distances greater than the critical distance, the received power drops proportionally to an inverse of the fourth power of the distance. It is obvious from Fig. 5 that for distances greater than the critical distance, the approximation formula (4) of the two-ray model completely agrees with the actual 2-ray model (2). For distances less than the critical distance the Friis formula gives better results than the two-ray approximation formula.

TABLE I. A MATLAB SCRIPT TO COMPARE THE FREE SPACE AND TWO-RAY PROPAGATION MODELS

```
f=600*10^6;  c=3*10^8;    lmd=c/f;
ht=50;  hr=2;  Pt=100;  Gt=1;  Gr=1;  i=1;
dc=4*pi*ht*hr/lmd;
for d=10:1:10^5
  dis(i)=log10(d);
  dlt=sqrt((ht+hr)^2+d^2)-sqrt((ht-hr)^2+d^2);
  Pr1b=(abs(1-exp(-j*2*pi*dlt/lmd)))^2;
  P1(i)=10*log10(Pt*Gt*Gr*(lmd/(4*pi*d))^2*Pr1b);
  P2(i)=10*log10(Pt*Gt*Gr*(lmd/(4*pi*d))^2);
  P3(i)=10*log10(Pt*Gt*Gr*(ht*hr/d^2)^2); i=i+1;
end
plot(dis,P1,dis,P2,'r:',dis,P3,'k--')
legend('2-Ray No Approx.','Free Space','2-Ray with Approx.')
xlabel('log10(d)'); ylabel('Received Power Pr [dB]')
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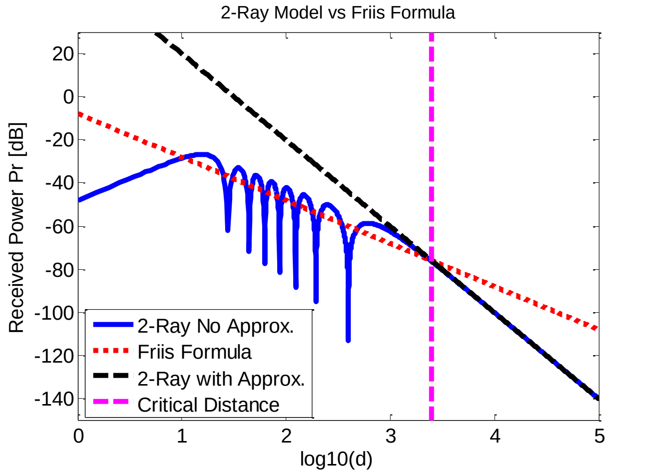

Fig. 5. The received power vs distance graph computed using the Friis formula and the 2-ray model (f=600 MHz, $P_t=100$ W, $G_t = G_r = 1$, h_t=50 m, h_r=2 m).

A student may use the MATLAB code in Table 1, change the values of the transmitted power P_t, the heights h_t, h_r and the gains G_t, G_r of the transmitter and receiver antennas, the wavelength λ and investigate their effects on the received power P_r and on the critical distance.

The last step in the course may be the investigation of radiowave propagation over non-smooth Earth's surface and through non-homogenous atmosphere. The virtual tool SSPE_GUI can be used for this purpose. This package is based on step-by-step numerical solution of the 2D parabolic equation using Fast Fourier transformation (FFT) and models one-way propagation problems. Instructions on how to use the tool and some characteristic examples were given in [6] and the user interface of SSPE_GUI is displayed in Fig. 6. A student may design non-flat terrain profiles, specify various refractivity profiles, and test their effects on the radiowave propagation.

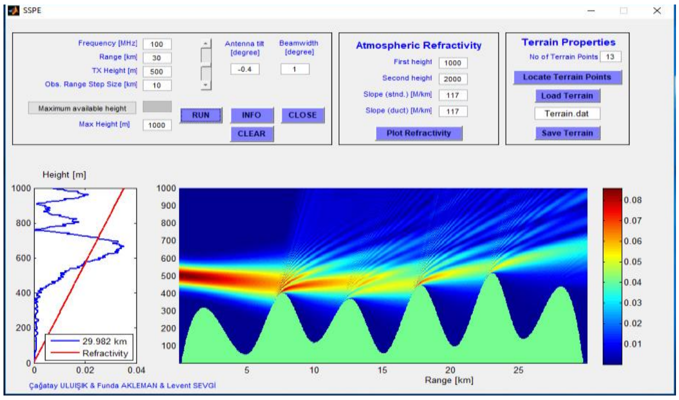

Fig. 6. The user interface of SSPE_GUI.

IV. CONCLUSIONS

Radiation characteristics of basic antenna elements and their arrays are visualized using the virtual tool ArrayGUI. Antenna terms such as beamwidth, element pattern, array factor, total radiation pattern, phased arrays, uniform / binomial excitations, broadside / endfire radiation are investigated. Radiowave propagation is also investigated using the free space model, the two-ray model and the split step parabolic equation (SSPE) model. Short MATLAB scripts and MATLAB-based simulation packages are introduced to visualize wave propagation.

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