Interactive visualization of new electromagnetic quantities

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Abstract

Recent development in classical electrodynamics has demonstrated the usefulness of different rotational and topological modes in the electromagnetic fields (angular momentum, polarization, vorticity *etc.*). Unfortunately, the visualization tools available to illustrate these electrodynamic quantities have hitherto been inadequate. Therefore we have developed a VTK and Python based interactive visualization tool, with working name EMVT (ElectroMagnetic Visualization Tool), targeted at visualizing precisely these modes.

In the near future, EMVT will be further developed to visualize and control live antenna systems, where electromagnetic field data is instantly received, calculated, and visualized from an antenna or a system of antennas. It will then be possible to see how the antenna properties change through direct user interaction in real time.

1 Introduction

Ever since Poynting in 1909 [Poynting 1909] predicted that electromechanical rotations of a shaft must be carried out by electromagnetic (EM) radiation, the rotational modes of the EM fields have received more and more attention. Recent development has shown that there are no less than three different types of rotational degrees of freedom embedded in the fields [Bergman et al. 2008; Allen et al. 2003]. In analogy with a planetary body (for instance the Earth), an EM beam can rotate around its own axis (spin angular momentum), rotate around an external axis (orbital angular momentum) and nutate due to the tilt of the spin axis compared to the rotational plane around the axis (*cf.* Earth nutation). These rotational properties can be investigated by performing different multiplicative operations between the EM fields, time, and the position vector, resulting in different conserved physical quantities [Jackson 1998; Noether 1918; Bergman et al. 2008]. These conserved quantities are carried by the fields and, hence, can be used for information extraction. This makes them very important in physics [Thidé et al. 2007], astronomy [Harwit 2003], and communication. The relevant conserved electromagnetic quantities can be found in Table 1.

Standard visualization methods (see Fig. 2) are in essence limited to visualizing the power density, which is adequate for studies of the linear momentum of the fields. However, it does not yield satisfactory insight into the behavior of the rotations in the fields, which on the other hand are, for instance, clearly visible in Fig. 1.

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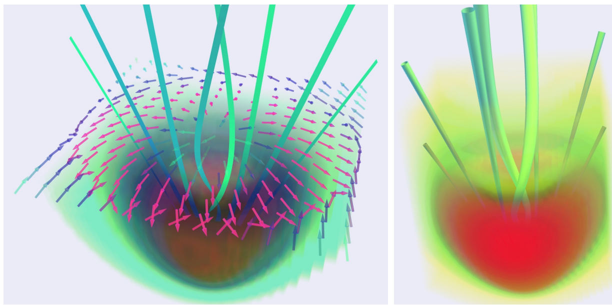

Figure 1: *The images show how the user can visualize the same data set differently by changing hue, saturation, and alphablend parameters, as well as using different visualization aids. The visualization aids used in the image to the left are volume rendering, stream lines with ribbon visualization, and a vectorial cut plane, whereas the image to the right only uses volume rendering and stream lines with tube visualization.*

2 Simulation setup

EM field rotations in the radio domain can be produced in a simple but powerful way with only a few antennas. Essentially, a polarized beam which also carries orbital angular momentum will have all of the three rotational modes embedded in the fields.

We have produced our raw data (EM vector fields) for the visualizations by using NEC2 [NEC2] and the geometry editor of 4NEC2 [Voors]. We placed ten identical, electrically short, crossed electric dipoles, 0.10 wavelengths (λ) above a perfect electric conduc-

Table 1: *Conserved Electromagnetic quantities, notation:* $u = \varepsilon_0(\mathbf{E}\cdot\mathbf{E}^* + c^2\mathbf{B}\cdot\mathbf{B}^*)/2$, $\mathbf{P} = \varepsilon_0 \operatorname{Re}[\mathbf{E}\times\mathbf{B}^*]$, $\mathbf{V} = -\varepsilon_0 \operatorname{Im}\left[\mathbf{E}\times\mathbf{E}^* + c^2\mathbf{B}\times\mathbf{B}^*\right]/2c$ *and* $w = 1\operatorname{Im}[\mathbf{E}\cdot\mathbf{B}^*]/Z_0$. *Abbrevations: AM = Angular Momentum, EM = Electromagnetic, Pol. = Polarization, Lin. mom. = Linear momentum,* ε_0 *= vacuum permittivity,* c *= speed of light,* Z_0 *= vacuum resistance.*

	Energies	Momenta	Angular Momenta
Usual	u	$\mathbf{P}$	$\mathbf{r}\times\mathbf{P}$
Phys. interp.	EM Energy	lin. mom.	AM
Pol. based	w	$\mathbf{V}$	$\mathbf{r}\times\mathbf{V}$
Phys. interp.	Pol. Energy	Pol. Vector	Spin orbital AM

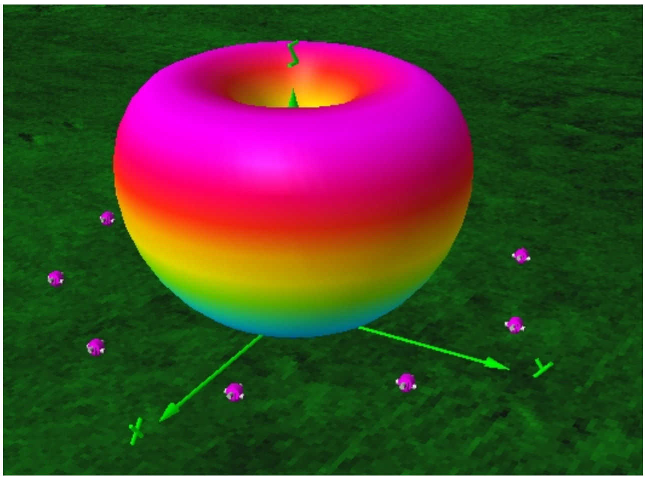

Figure 2: *A 3D visualization of the so called antenna diagram, corresponding to the structure of the electromagnetic power density produced by the ten element circular antenna array. Here, we see the general behavior of the array but there is no information about the rotations embedded in the fields. The image was created by 4NEC2.*

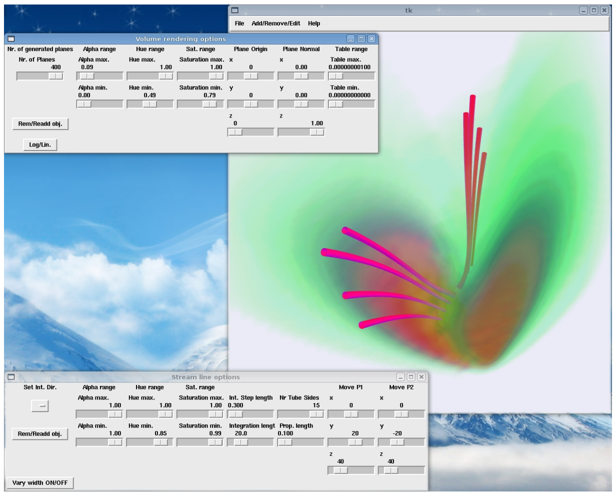

Figure 4: *A screen shot of EMVT. The user controls two objects which visualize the polarization and nutation of an electromagnetic field created by our simulation setup. All VTK objects here have either color transfer functions or so called vtkLookuptables, which control the hue, saturation, alpha blending, etc of the object. These properties, and others, can be changed interactively by the user.*

tor in a phased circular array; see Fig. 3. The largest dimension of the array is $D = \lambda$. The dipole elements are fed in such a way that a perfectly circularly polarized field, which also carries orbital angular momentum number proportional to unity, *i.e.*, $l = 1$, is created. The dimensions of the box, where the fields are calculated are: $-14\lambda < X < 14\lambda$, $-14\lambda < Y < 14\lambda$, and $0 < Z < 25\lambda$.

3 General visualization methods

3.1 VTK

We chose to use The Visualization ToolKit (VTK) [Kitware ; Kitware 2006] since it is an open source and freely available software system for computer graphics and visualization that supports a wide variety of visualization algorithms including scalar, vector and volumetric methods. Both the design and implementation of VTK has been strongly influenced by object oriented principles, which makes it relatively easy to use even though the library literally contains thousands of classes. However, the huge number of classes is probably a big threshold to overcome for those who wants to create their own visualizations for the first time and therefore some would for instance prefer Paraview [Squillacote 2008], which is an open source application designed to visualize large data sets. Nonetheless, we wanted to maintain full control over the whole visualization process and for our specialized application we wanted to be able to compute the new electrodynamic quantities within our application, instead of having a preprocessor stage. Furthermore, Python [Python ; Lindblad 2006] was used as the main programming language since it is object oriented and can handle data in an efficient way, *i.e.* it is easy to write a program using Python that reads the ascii output of NEC2 and converts it to the internal representation in VTK as well as it computes other quantities.

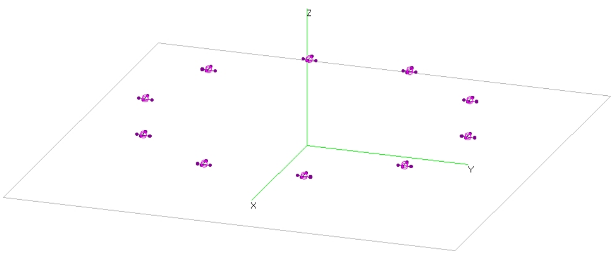

Figure 3: *Ten electrically short crossed electric dipoles in a circle, creating a field carrying a total OAM $l = 1$ and spin $s = 1$. The image is from the geometry editor of 4NEC2.*

3.2 Methods used in EMVT

There are in principal five different types of visualization possible in EMVT:

1. **Volume rendering** – This type of rendering gives good insight into how the scalar quantities behave, where the colors are proportional to the scalar values. The intensity of vector fields (vector squared in each point) can also be visualized in this manner.

2. **Isosurfaces** – Scalar values or the amplitudes of a vector field can be illustrated by drawing a surface over all constant values of the considered quantity.

3. **Vector arrows** – Vector fields can be simply illustrated by vector arrows. The arrows can be normalized to be of the same length, where the coloring can be proportional to the length of the vectors or one of the scalar quantities.

4. **Cut planes** – Cut planes, can be used to cut both vector fields and scalar values. These can be oriented and placed as the user wishes.

5. **Flow lines** – Inspired by wind tunnel data visualizations, a "string" is let loose and guided by the vector field. In this way it is easy to see the flow of the field considered.

The visualization tools introduced in EMVT can be combined in whichever manner that suits the user and for any of the electromagnetic quantities. What is also an important feature of EMVT is that

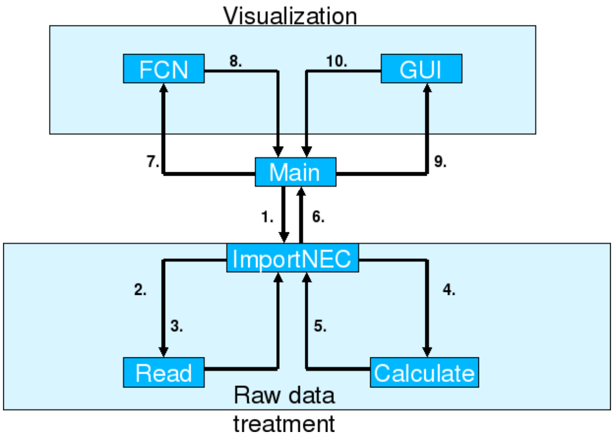

Figure 5: *This illustration shows the flow chart of EMVT. The program runs ten steps before an actual image is displayed.* ***1.*** *User input data files;* ***2.*** *Two strings, address to files;* ***3.*** *Dimension, NumberOfVectors, 4 × vtkDoubleArray, 2 × vtkPoints;* ***4.*** *nrVectors, 4 × vtkDoubleArray, 1 × vtkPoints;* ***5.*** *Treated data, 12 × vtkDoubleArray;* ***6.*** *Treated data, 12 × vtkDoubleArray, 1 × vtkPoints, nrVectors, dimensions;* ***7.*** *User chooses visualization tool and data to visualize, 1 × vtkDoubleArray;* ***8.*** *VTK objects and parameters;* ***9.*** *VTK objects and parameters; and* ***10.*** *VTKActor;*

it is possible to visualize as many different electromagnetic quantities at the same time in the same window as the user needs or wants. This is important since a general user of EMVT will have had first hand experience of the energy and linear momentum visualizations, for instance as in Fig. 2, but no experience of the visualization of the other EM quantities. When both the linear momentum and the angular momentum is visualized in the same image, the first visualization will provide a reference for the user, from which the angular momentum visualization can be put into context.

4 EMVT program structure

The main structure of EMVT is illustrated in Fig. 5. It consists of two different parts, the raw data processing, which reads data ("Read" class) and makes the necessary calculations ("Calculate" class) and the visualization classes ("FCN" and "GUI" classes). The raw data processing code is written in native Python whereas the visualization classes are written using VTKs class library. For

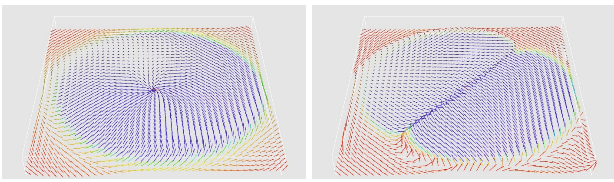

Figure 6: *These two images show how the nutation.* $\mathbf{r} \times \mathbf{V}$. *of the electromagnetic field is affected when the polarization of the generated field is changed from perfectly circular (left image) to linearly (right image) polarization.*

each visualization type, *i.e.* volume rendering, cutplanes *etc.*, there exist two classes. The function class (FCN), which creates the necessary VTK objects and parameters, and the graphical user interface class (GUI), which in turn creates the GUI to control the VTK objects created by the FCN class. A screenshot of an EMVT run, where the user is interactively controlling two different objects to

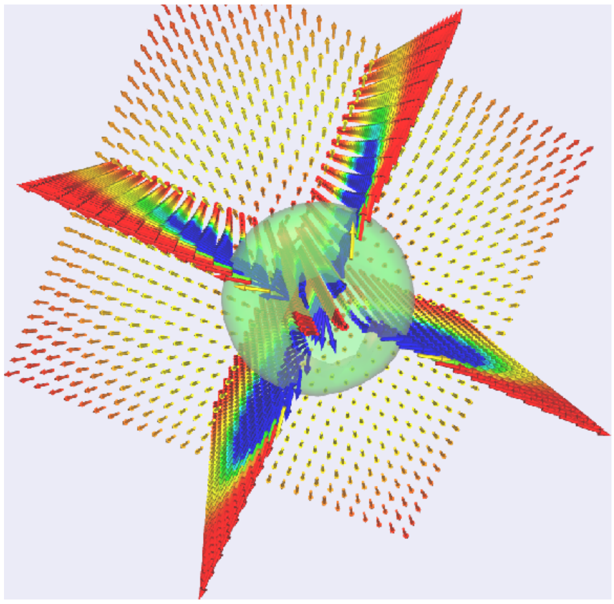

Figure 7: *This image visualizes the linear momentum (vectorial cut planes) and electromagnetic energy (isosurface).*

enhance the visualization of two electromagnetic quantities related to polarization, can be seen in Fig. 4. Other screenshots of the visualizations created by EMVT can be viewed in Fig. 1, 6 and 7. These images show different electromagnetic quantities visualized in different ways. Note the clear rotational patterns visible in Fig. 1 and 6, which visualizes the polarization, nutation and angular momentum of the field, whereas Fig. 7, which visualizes the Poynting flux (or linear momentum) with more traditional methods, gives no direct insight into the rotational structures. Furthermore, by comparing Fig. 1 and Fig. 8 the different rotational properties of the field can be clearly shown and thus the disparate nature of the spin rotations and orbital angular momentum rotations.

5 Discussion and future

Visualization of data is an indispensible tool for any physicist or scientist in general. By studying the graphs and visualizations created from the data the user can efficiently extract information of how the system works and, above all, get a feeling for it. Connections between different parameters and physical quantities can be enhanced, which otherwise would not be as obvious if one only studies mathematical expressions or the raw data sets. The need to be able to interactively tune and change visualization parameters as the alpha factor *etc.* is vital in order to enhance the structure one wants to see. Furthermore, in this application all of the visualized quantities, where calculated from the same dataset. This is an important feature since, generally, the output of any EM simulation program is typically the electric and magnetic vector fields. However, all of the physics of the system cannot be seen by only visualizing the fields. One needs to perform several calculations before the physical, observable, quantities of interest which reveal such behavior as rotations *etc.* are found.

5.1 Future

This visualization tool (EMVT) has the potential to be further developed and used on live antenna systems. A live antenna system can be anything from a single receiving antenna for an FM radio

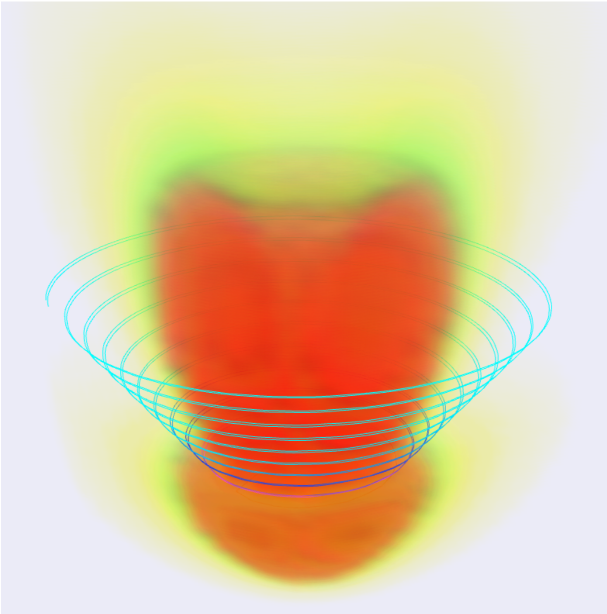

Figure 8: *This image shows the angular momentum intensity,* $|\mathbf{r} \times \mathbf{P}|^2$*, (volume rendering) and the angular momentum flow,* $\mathbf{r} \times \mathbf{P}$*, (stream lines) of the fields created by the described antenna system.*

to huge radio telescopes such as LOFAR [LOFAR]. By calculating the fields in a small volume around the receiving antenna or antennas from the currents induced on them, the user can visualize how the field and all its properties behave. Furthermore, if a controller is created for the receiving antenna then the user can instantly see how the antenna and different electromagnetic quantities change during the interaction with the application.

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