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Scientific visualization of geophysical simulation data by the CAVE VR system with volume rendering

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Abstract

As the size and complexity of the simulation data increase, the need to visualize the data in three-dimensional (3D) space is growing in the geophysical community. The modern virtual reality (VR) technology provides a technical solution to the demand. Among modern VR systems, the CAVE provides the most effective VR environment. We have developed a VR visualization software for the CAVE system that incorporates the volume rendering visualization method. Implementation of a high speed volume rendering using the texture-map technique in the CAVE and its applications to various geophysical simulation data produced by Earth Simulator are examined.

Keywords: Volume rendering; CAVE; Visualization

1. Introduction

The development of the supercomputer technology enables us to perform large scale computer simulations of various geosystems from the magnetosphere down to the mantle and the core. The growing size and complexity of the output data of the simulations indicate the definite approach to the real Earth system, but it also means an increasing burden to the researchers for the data analysis or visualization. Simulation researchers these days need a technological innovation for effective scientific visualization that matches the advanced computational technology.

Since most of the large scale geophysical simulations today are performed in three-dimensional (3D) computational space, their data analysis inevitably requires a 3D or stereoscopic display apparatus. We also need a sophisticated user-interface to control the view point. The standard mouse controller for a personal computer (PC) is not convenient enough to choose, set, and adjust the camera position and direction when we want to intuitively observe highly complicated visualization objects in the stereoscopic display system.

This problem of effective view control is already solved in the modern virtual reality (VR) technology. In a VR system, the viewpoint is automatically, and intuitively, controlled by the so-called head tracking system. The position and direction of the observer's eyes are monitored by a tracking devise. The viewpoint in the virtual 3D computer graphics world is adjusted in accordance with the viewer's head position in the real world.

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When a VR system uses a large curved 3D display screen or a set of plane screens to surround the viewer's body, it is called an immersive display system. One of the most successful immersive VR systems is the CAVE (Cruz-Neira et al., 1993). The central part of the CAVE is a room-sized cube that is composed of three wall screens (front, right and left) and another screen for the floor (Fig. 1). The viewer or user who is standing on the floor screen is surrounded by the four screens. Stereo images are generated by a graphic workstation and projected onto the four screens.

The CAVE is not merely a large (and actually expensive) 3D data viewer. All the images are automatically re-rendered based on the viewer's position and viewing direction in real time. As the viewer walks inside the CAVE room, looks around, and even jumps, all the four images on the walls and the floor are automatically adjusted to the viewer's position at each moment. The high speed graphic workstation makes the quick response possible. All the four stereo images are seamlessly connected on the boundaries between the screens.

The viewer in the CAVE room has a small portable controller called wand. Since the position and direction of the wand are also automatically tracked as the head, one can use it as an effective user-interface apparatus in the CAVE's VR space as a kind of 3D mouse.

We have been developing our own visualization software "VFIVE" (Kageyama et al., 1999, 2000) as a general purpose visualization software for the CAVE. It has basic visualization methods such as (i) isosurface, (ii) contour lines, (iii) color slice, and (iv) particle tracing and so on (see Table 1).

Fig. 1. Screens of the CAVE system installed at Earth Simulator Center. Stereoscopic, color images are seamlessly projected onto the wall screens from the projectors behind the walls. Another stereo image is projected onto the floor from a projector on the ceiling.

Table 1
The main visualization methods of the VFIVE

For vector field	Field lines Local arrows	Particle tracer Spotlighted snow	Tubes Stream surfaces
For scalar field	Isosurface	Local slice Contour lines	Color contour Volume rendering

To briefly explain the basic function of the VFIVE, let us take the particle tracer (or stream lines) for example since it is the most characteristic visualization method of the VFIVE. When an user in the CAVE room, immersed in the simulation data, presses a wand button, a virtual particle appears on the tip of the wand. When he/she releases the button, the virtual particle leaves the wand tip following the flow field of the simulation data. By observing the particle motion in 3D space under his/her nose, one can intuitively grasp the possibly complicated flow vector field. The viewer can release tens of particles by repeating the button pressing with slowly moving the hands to shift the starting points. When the target field is a scalar field, one can make use of the VFIVE's other visualization functions, for example, isosurface. We have applied the VFIVE in the CAVE to various geoscientific data generated by Earth Simulator such as mantle convection, geodynamo, and global circulation models of the atmosphere and ocean.

We have found that the VR visualization is very powerful as we expected, but we also learned from the experience that the visualization of scalar data by means of the isosurface method needs an improvement. The problem of an isosurface visualization is that it shows the spatial structure of the data for only one specific value. It is possible to draw multiple isosurfaces with semi-transparent colors for multiple value, but it results in the generation of massive polygons in total and that inevitably reduces the rendering speed of the computer graphics. On the usual visualization environment of PC's, one can wait several seconds or more to finish the rendering, but in the CAVE, every image should be rendered within a fraction of a second since all the images should be refreshed every moment to follow the viewer's motion. We concluded that we had to adopt another approach to the scalar data visualization, that is the volume rendering (Drebin et al., 1988).

The volume rendering is a visualization method for 3D scalar data contrived in late 1980s. This method makes the entire data being visible at the same time by putting a color with opacity at the each spatial point in accordance with the scalar value there. In contrast to the isosurface method, the volume rendering enables us to grasp the whole distribution of the 3D scalar data at once, if the colors and opacities are properly controlled.

It is an attractive, actually not new, idea to implement the volume rendering in the CAVE (Brady et al., 1995; Boyles and Fang, 2003; Schulze and Forsberg, 2005; Suzuki et al., 2005). Our interest here is to confirm the applicability and efficiency in the visualization of geoscientific simulation data. We implemented the volume rendering as a part of the VFIVE's framework.

2. Volume rendering in virtual reality

The most basic algorithm of the volume rendering is the so-called "ray cast" method (Fig. 2). In this method, in order to generate an image composed of $N \times M$ pixels, one casts totally $N \times M$ rays. Each ray starts from the viewer's eye position, goes through a pixel of the image on the screen, and runs through the scalar field to be visualized. As the ray proceeds through the scalar field, the data value on each sampling point is accumulated after it is converted into a color with opacity. The color and opacity are determined from the scalar value through pre-defined rules called transfer functions. Since this ray cast integration is repeated for $N \times M$ times to generate a full image, the ray cast method is computationally demanding.

In order to realize the volume rendering visualization in the CAVE room, the rendering speed is critically important because the view point changes every moment as the user walks in the CAVE room. The refresh rate of the image should be at least several frames per second or more to keep the CAVE's high quality VR environment.

We have adopted another approach to the volume rendering called "texture-map technique" (Schroeder et al., 2002; Cabral et al., 1994). This technique is an application of one of the most popular computer graphics methods called texture mapping.

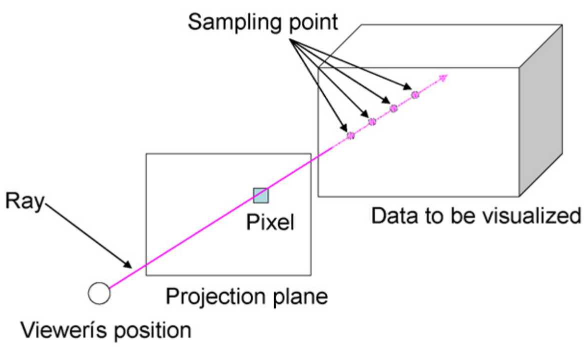

Fig. 2. The basic algorithm of the ray-cast method for the volume rendering. This method is computationally too demanding to realize the real time volume rendering in the CAVE.

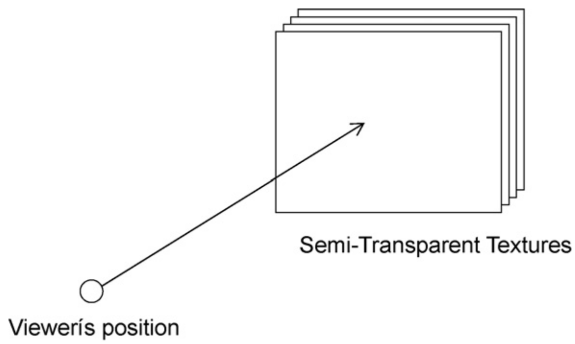

Fig. 3. Another method for the volume rendering based on the texture-map technique. This method is fast enough to realize the real time volume rendering in the CAVE.

In a standard texture mapping, a two-dimensional image, or a picture, is pasted or mapped onto a rectangle, or more generally, a polygon in the 3D computer graphics world. The picture may be semi-transparent. When a sequence of such semi-transparent images are mapped onto layered polygons one by one from back to front, the images are blended in effect for a viewer (see Fig. 3). This is the principle of the volume rendering based on the texture-map technique. This texture-map technique is fast enough to realize the real time volume rendering for a scalar data even in the CAVE. Brady et al. (1995); Boyles and Fang (2003); Schulze and Forsberg (2005); Suzuki et al. (2005) used this kind of technique in the CAVE.

We have integrated the volume rendering based on the texture-map technique into the VFIVE framework, with an additional user-interface for the volume rendering to control the transfer functions of color and opacity in the CAVE room (see Fig. 4). We have found that this user-interface is very effective to reduce the burden of data analysis in the CAVE room.

In our CAVE system we can use, for example, the volume rendering for temperature (i.e., scalar) field and the stream lines for the flow (i.e., vector) field at the same time because our newly developed volume rendering is fully integrated into the VFIVE framework. It is common in the data analysis of geophysical simulations that one wants to analyze a scalar field and a vector field at the same time since their correlation is sometimes very important.

3. Applications to geophysical simulation data

3.1. Geodynamo

The first example of the application of our VR visualization is to a geodynamo simulation. Fig. 5(a) shows

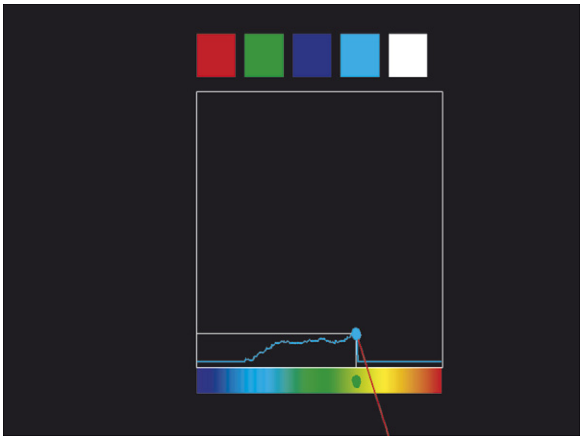

Fig. 4. Color and Opacity Editor in the CAVE. One sees this Editor panel on the CAVE's front wall. The parameters for the volume rendering are easily controlled by a virtual laser beam emitted from a small portable controller in hand.

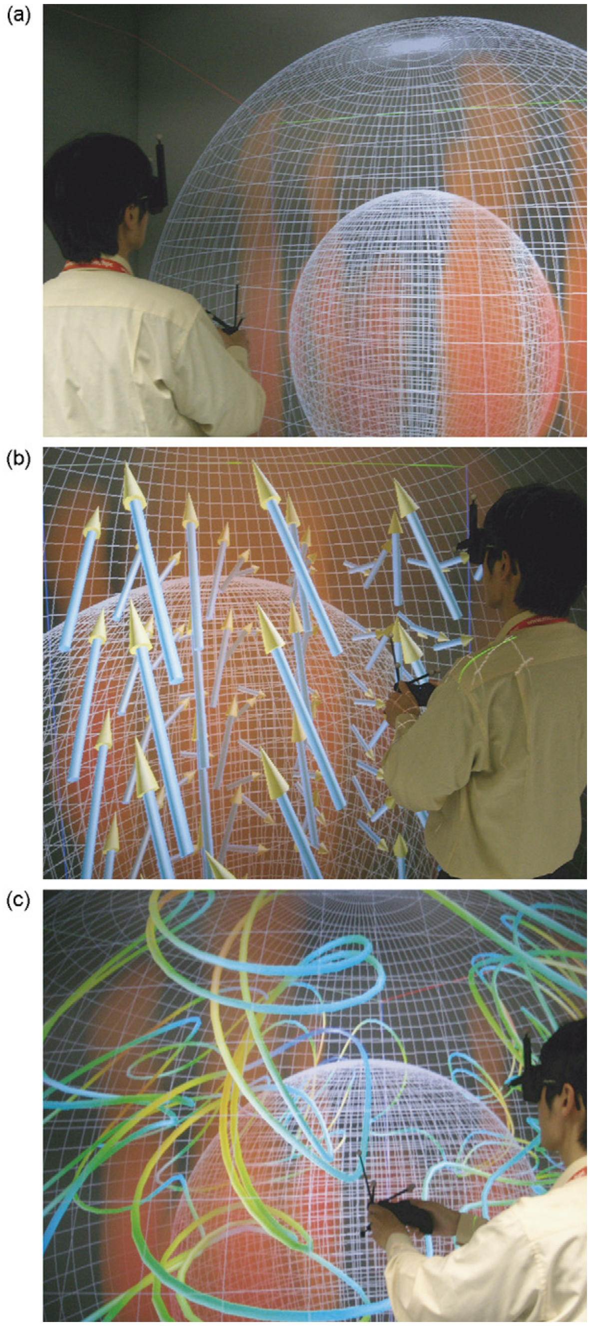

Fig. 5. (a) A volume rendering image in the CAVE. The z-component of the vorticity in a geodynamo simulation is visualized. (b) Same data as (a). Superimposed visualization of the local arrows for the convection flow and the volume rendering for the vorticity. (c) Tube visualization for the convection flow and the volume rendering for the vorticity.

a snapshot of volume rendering image of the convection motion in the core. The semi-transparent red columns correspond to columnar convection cells aligned to the Earth's rotation axis due to the Coriolis force. The volume rendering was applied to the scalar field of the z-component of the vorticity, ω_z. The transfer functions of the color are set so that the negative component of ω_z are visualized as the red volumes. In the picture, two spheres are shown with wire frames, which denote the simulation boundaries; the inner core and core-mantle boundary.

We also tried to visualize these convection columns by using the isosurface method applied to the ω_z field. One of the problems of the isosurface method in this case was that the isosurface polygons tend to hide other important visualization objects such as stream lines and flow arrows visualized by VFIVE. We have found that the volume rendering is very useful in this visualization since the 3D images are intrinsically semi-transparent and we can easily observe other visualization objects through them. Fig. 5(b) shows such an example. In this figure, the convection of flow field is visualized by a bunch of the small arrows. The length and direction of each arrow shows the local flow vector. We can see all of the arrows through the semi-transparent volume rendered ω_z column. Note that in the real CAVE environment, everything looks in 3D and the viewer in the CAVE feels strong reality due to the immersive and stereoscopic images with the head tracking system.

The arrows in Fig. 5(b) are "floating" around the columnar red "cloud". That is a localized negative-ω_z region, or rotating convection cells in the anti-cyclonic direction. The distribution of the arrows' orientation in the horizontal direction certainly shows that they are rotating in the opposite direction of the Earth's rotation. New information comes when we observe the orientation of the arrows in the vertical direction or their parallel component to the rotation axis. The arrows in the red cloud have upward (northward) direction, that means that the fluid in this anti-cyclonic convection columns are flowing in a corkscrew trajectory with negative helicity.

The observation of the helical structure of the flow in the convection columns are confirmed by superimposing the volume rendering image of ω_z with another visualization method for the flow called Tubes in which the vector field is visualized by a stream line with a finite radius or a tube (see Fig. 5(c)). We can see from this visualization that the helical structure of the convection field is prevailing in the northern hemisphere. If we used the isosurface as the visualization method for the scalar field of ω_z, we would miss this helical structure of the flow since the most of the arrows and stream lines are hidden in the opaque isosurface.

We might be able to visualize the 3D distribution of ω_z by generating multiple semi-transparent isosurfaces for different values ($\omega_z = \omega_{z0}, \omega_{z1}, \omega_{z2}, \ldots$) instead of the volume rendering, but the number of the total polygons that constitute the surfaces may become enormous and that makes this method impractical. On the other hand, the rendering speed of the volume rendering method is not strongly dependent on the complexity of the data.

Another demerit of using the multiple isosurfaces method to visualize a scalar data is that it is difficult to find regions of steep gradient in the data. We would have to try many sets of isosurface values in order to find the strong gradient of the scalar field. On the other hand, it is easy to find such a region by the volume rendering. All we have to do is to just specify a proper transfer functions of the color and the opacity. In our volume rendering software incorporated in the VFIVE framework, it is easy to control the transfer functions standing in the CAVE room by making use of the user-interface described in the previous section.

3.2. Mantle convection

Here, we show an application to the visualization of a mantle convection simulation (Kameyama and Yuen, 2006). Fig. 6 shows the distribution of the lateral thermal anomaly or deviation from the average temperature at each depth visualized by the volume rendering.

Fig. 7(a) shows a certain local region with the velocity arrows. The combination of volume rendered semi-transparent objects for scalar data and the polygon-based visualization (the arrows) helps researchers to understand the data structure. The power of this combination is enhanced by the fully interactive nature of 3D analysis of the VFIVE: one can observe flow vector at arbitrary region by just pressing a button of the wand controller.

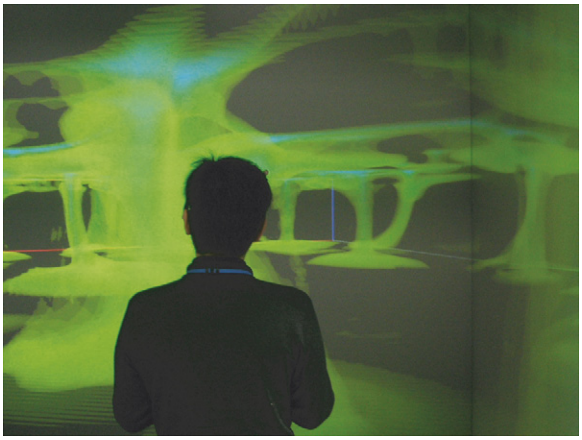

Fig. 6. The distributions of the lateral thermal anomaly. (Data courtesy of Dr. Masanori C. Kameyama at Earth Simulator Center.)

(a)
(b)

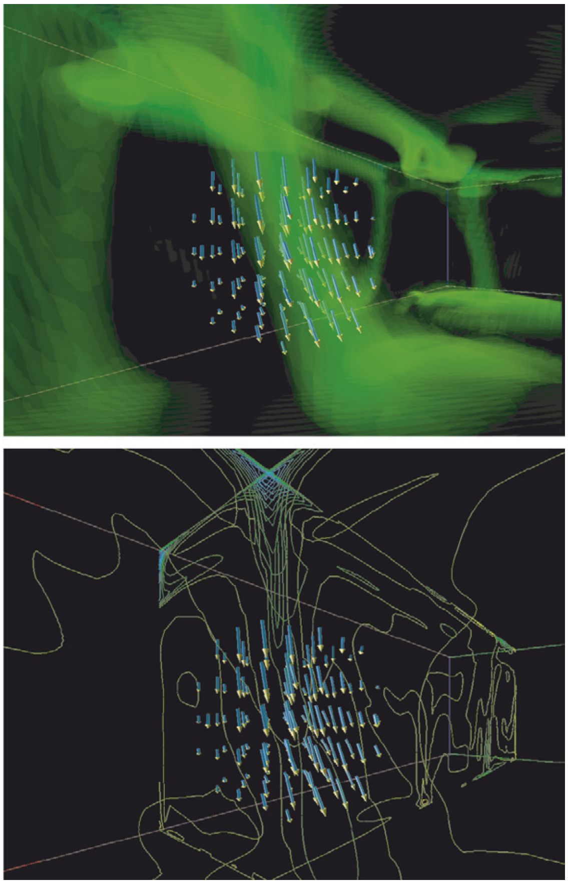

Fig. 7. (a) CAVE visualization of the mantle convection for temperature (volume rendering) and the flow velocity (arrows). (b) CAVE visualization of the same data as (a) but by the contour lines instead of the volume rendering.

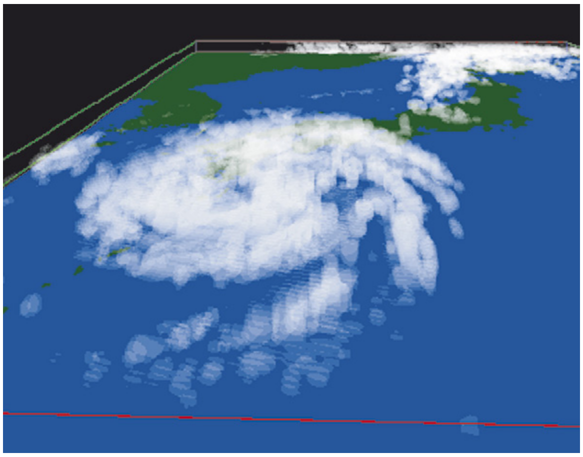

Fig. 8. A CAVE visualization of typhoon by the volume rendering. (Data courtesy of Dr. Keiko Takahashi at Earth Simulator Center.)

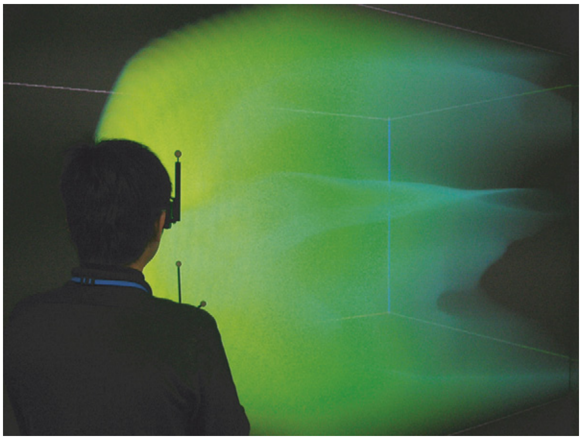

Fig. 9. A volume rendering of the pressure distribution of the Earth's magnetosphere in the CAVE. (Data courtesy of Prof. Tatsuki Ogino at Nagoya Univ.)

To compare with the volume rendering, we show in Fig. 7(b) the same region of the same data as Fig. 7(a) but with different visualization method (the contour lines of two orthogonal slices) of the VFIVE instead of the volume rendering. It is obvious that the volume rendering is more appropriate for visualization in this case.

3.3. Typhoon

Fig. 8 shows an applied image to a typhoon simulation. The data was produced by a high resolution coupled non-hydrostatic atmosphere-ocean model developed at Earth Simulator Center. While this kind of typhoon simulation data has a rich 3D structure, meteorological simulation researchers tend to use traditional two-dimensional visualization tools. The data is worth being explored by fully interactive 3D analysis in the CAVE.

The swirl structure is clearly seen in Fig. 8. Owing to the character of the volume rendering method and the proper transfer function that is interactively tuned in the CAVE room, researchers can observe their data as if the real clouds exist there. The volume rendering method especially fits the representation of vague distribution such as cloud. This example suggests that the volume rendering in the VR systems could provide a powerful tool for the meteorological data analysis.

3.4. Earth's magnetosphere

The last example of our applications is the visualization of global simulation of the magnetosphere in which the magnetohydrodynamic equations for plasma are solved. There are at least three important scalar variables (pressure, mass density and temperature) and two vector fields (magnetic and velocity fields). These variables are relating intimately each other and researchers need to derive physical insight from the correlation between such many variables.

The magnetosphere has a very rich complex structure. The supersonic plasma flow of the solar wind deforms the Earth's dipole field and generates characteristic structures with the bow shock, magnetopause, magnetotail and the plasma sheet. The visualization is, therefore, indispensable in the data analysis of the global simulation of the magnetosphere.

Fig. 9 shows the pressure distribution by the volume rendering in the CAVE. The bow shock, plasma sheet and the magnetosheath are all clearly captured in this visualization. It would be almost impossible to visualize all those structures at once by means of the isosurface method.

4. Conclusion

We have developed a volume rendering program for the CAVE VR system. By making use of the texture-map technique, we have successfully implemented a high speed volume rendering with the real time response that is indispensable for the CAVE's VR visualization. This volume rendering method is incorporated into the VFIVE framework that is our original visualization software for the CAVE. By combining newly developed volume rendering method and other VR visualization tools in the VFIVE, we have found that the VR can be a powerful visualization environment for various kinds of geophysical 3D simulations.

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