Development of the Virtual Earth's Magnetosphere System (VEMS)

Ken T. Murata[1]*, Kazunori Yamamoto[1], Daisuke Matsuoka[1], Eizen Kimura[1],
Hiroshi Matsumoto[2], Masaki Okada[3], Toshifumi Mukai[4], John B. Sigwarth[5],
Shigeru Fujita[6], Takashi Tanaka[7], Kiyohumi Yumoto[8], Tatsuki Ogino[9],
Kazuo Shiokawa[9], Nikolai A. Tsyganenko[10], James L. Green[10]
and Tsugunobu Nagai[11]

[1]*Center for Information Technology, Ehime University, 3, Bunkyo-cho, Matsuyama 790-8577*
[2]*Research Institute for Sustainable Humanosphere, Kyoto University, Gokasho, Uji 611-0011*
[3]*National Institute of Polar Research, Kaga 1-chome, Itabashi-ku, Tokyo 173-8515*
[4]*Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency,
3–1–1, Yoshinodai, Sagamihara 229-8510*
[5]*Iowa University, Iowa City, Iowa 52242, U.S.A.*
[6]*Meteorological College, 7–4–81, Asahi, Kashiwa 277-0852*
[7]*Graduate School of Sciences, Kyushu University,*
[8]*Space Environment Research Center, Kyushu University,
6–10–1, Hakozaki, Higashi-ku, Fukuoka 812-8581*
[9]*Solar-Terrestrial Environment Laboratory, Nagoya University, 3–13, Honohara, Toyokawa 442-8507*
[10]*Goddard Space Flight Center, National Aeronautics and Space Administration, Greenbelt Road,
Greenbelt, MD 20771-0001, U.S.A.*
[11]*Tokyo Institute of Technology, 2–12–1, O-okayama, Meguro-ku, Tokyo 152-8550*
Corresponding author. E-mail: murata@cs.ehime-u.ac.jp

Abstract: We have constructed a new research environment for geo-space science based on 3-D visualization tool and network database; Virtual Earth's Magnetosphere System (VEMS). With an interactive research environment researchers can visually understand structures of the Earth's magnetosphere using VEMS. On the VEMS, computer simulation results and observation data are simultaneously visualized, having a potential to data assimilation for geo-space studies in the future. Since the VEMS deals with time-dependent data, it also helps researchers to study dynamics of the Earth's magnetosphere. We found that immersive data analyses are possible using the VEMS on a virtual reality system.

key words: computer simulation, Earth's magnetosphere, 3-D visualization, network database, satellite and ground-based observation

1. Introduction

There are two major research methods for geo-space science; computer simulations, satellite observations, and remote ground-based observations. Both methods have advantages and disadvantages: Computer simulations can provide data in whole time

and space in the simulation domain.   However, since they are based on model equations, the simulation results are not necessarily accurate.   On the other hand, satellite observation data are hopefully more accurate.   However, the data are restricted in time and space.   To combine both methods is important in order to develop our understandings of the structure and dynamics of geo-space. 3-D visualizations would be effective for combinations and analyses of both data (Murata *et al.*, 2004).

So far many global MHD simulations have been 3-D visualized (*e.g.*, Winglee *et al.*, 1998; Ogino, 2002; Shao *et al.*, 2003).   Recently Boston University (Glenn, 2004) demonstrated 3-D global MHD simulations on a virtual reality system at the SC2004 conference (SC04 Home page, 2004).   These are visualizations of simulation data, but satellite or ground-based observation data are not included.

In the present study, we propose a new research environment for geo-space science. This system is named VEMS (Virtual Earth's Magnetosphere System).   The basic concept of the VEMS is "to reproduce the past Earth's magnetosphere virtually in a personal computer".   It visualizes both satellite and ground-based observation data and global MHD simulation data together in 3-D space and 1-D time domain.

2.   Backgrounds for geo-space science

2.1.   Satellite observations

During the final decade in the 20th century, most of the satellite observations for geo-space were still *via* singular spacecraft.   In the near future, many missions will be with multi-spacecraft.   To study the static or dynamic structures of the Earth's magnetosphere *via* simultaneous multipoint observations, we often map the observation data on their orbits on 2-D planes (as will be shown in Fig. 2c).

However, as the number of spacecraft increase, the mapping results become complicated and their 3-D structures would be hard to be recognized.   In case of the studies to compare spacecraft observation data with ground-based phenomena on the Earth, 3-dimensional relative locations of the spacecraft are important.   For example, if one compares the regions of aurora breakup on the Earth with plasma jet observed by spacecraft located in the magnetotail, one may be interested in the footpoint of the magnetic field line on the Earth from the spacecraft (as will be discussed in Fig. 6).

2.2.   Computer simulations

During these two decades, many space plasma computer simulations were one- or two-dimensional.   However, as power and performance of super computers develop, the data sizes in the computer simulations become larger and larger.   During these 30 years, computational power of super-computers shows exponential progresses according to Moore's law (Intel Research, 2004).   Both main memory size and data storage size also show tremendous developments.   At the SC2004 conference, the peak values of super-computers are presented (SC04 Home page, 2004).   The best performance of super-computers, Blue Gene/L, measured by the Linpack benchmark was 72 TFlops. This CPU power is as twice as of the Earth Simulator in Japan (The Earth Simulator Center, 2004) which used to be at the top from 2002 to 2003.

2.3. Requirement to introduce

Through the above discussions on the background for geo-space science, it is implied that we should introduce new information technologies (IT) in this research field.   To compare and analyze a variety of data, we need an integrated system for data-download, data-read, data-plot and data-analysis. Recently powerful super-computers yield a huge size of data, and most of them are in 3-D format.   The visualization of simulations must be, therefore, in 3-D format since it is not easy to get 3-D images of the magnetosphere from 2-D plots.

In the next section we discuss a data analysis and reference system which has been developed by some of the present authors.   Therein a network database technology plays an important role.   Using the network database, in the present paper, we propose a 4-dimensional data visualization and analysis system in Section 4.   Both observation data and simulation data are to be visualized in 3-D space and 1-D time via visualization techniques and network database.

3.   STARS (Solar-Terrestrial data Analysis and Reference System)

3.1. Concept of STARS

In 1992, under the collaborations between the NASA, the ESA and the ISAS, an international project started, which is called the ISTP (International Solar-Terrestrial Physics) project.   In the project, many satellites are launched and observe the wide area in the geo-space and interplanetary regions.   The more scientific satellites are launched, with higher quality and quantity the data are provided by the satellites.   The software programs to analyze and plot the data become complex as more data are included into the programs.   A new software system was required that refers to and analyzes such a wide variety of data.

Some of the authors (Murata, Kimura and Yamamoto) have been developing a data analysis system for satellite and ground-based observation data for solar-terrestrial physics: Solar-Terrestrial data Analysis and Reference System (STARS) (Murata, 2003).   The STARS application works with a wide variety of spacecraft data and ground-based observation data.   The construction of the STARS is fully based on an object-oriented software methodology that is called Object Modeling Technique (OMT) (Rumbaugh, 1991).   It is usually said that the addition of new program, class and function is rather easy if a system is designed with the OMT.

3.2. Properties of STARS application

Figure 1 is a network configuration of the STARS application, the STARS meta-database and data sites for solar-terrestrial physics observations.   The STARS meta-database provides meta-information of observation data files managed at the observation data sites (Murata *et al*., 2002; Murata, 2003).   Users download data files through the STARS application.   The downloads are done backend of the STARS application, thus users don't know where the data files are managed over the Internet. In December 2004, the numbers of mission record, data record and data file record are 25, 140 and 1,219,056, respectively.   These numbers still continue to increase.
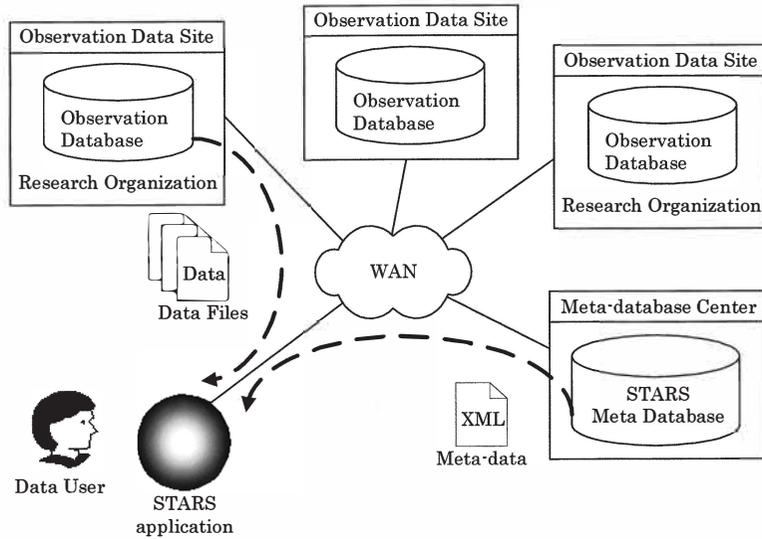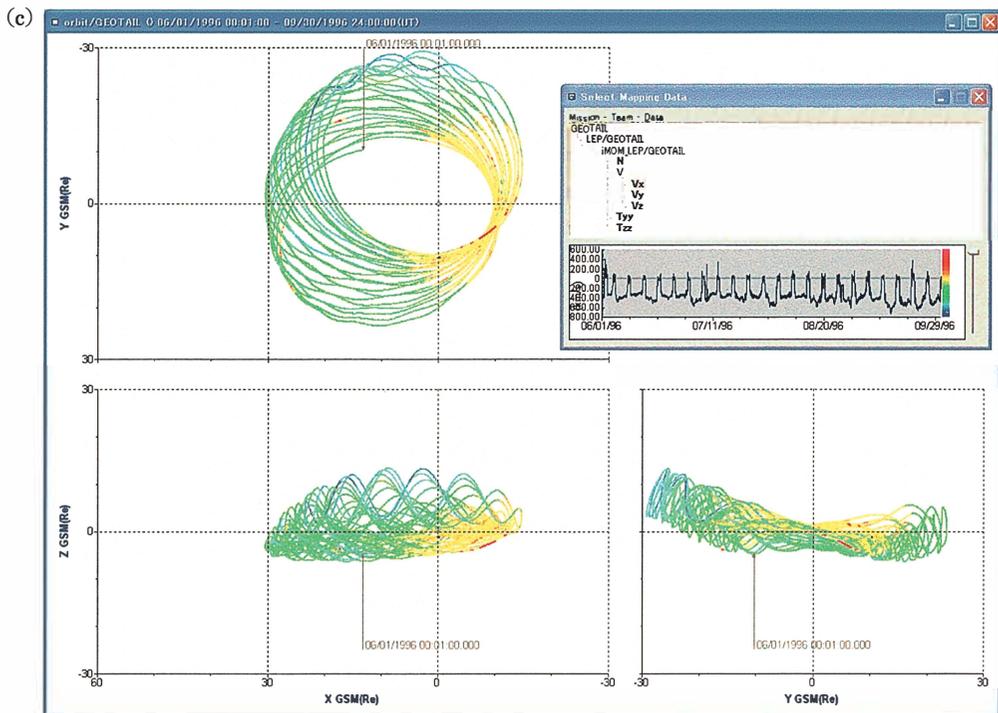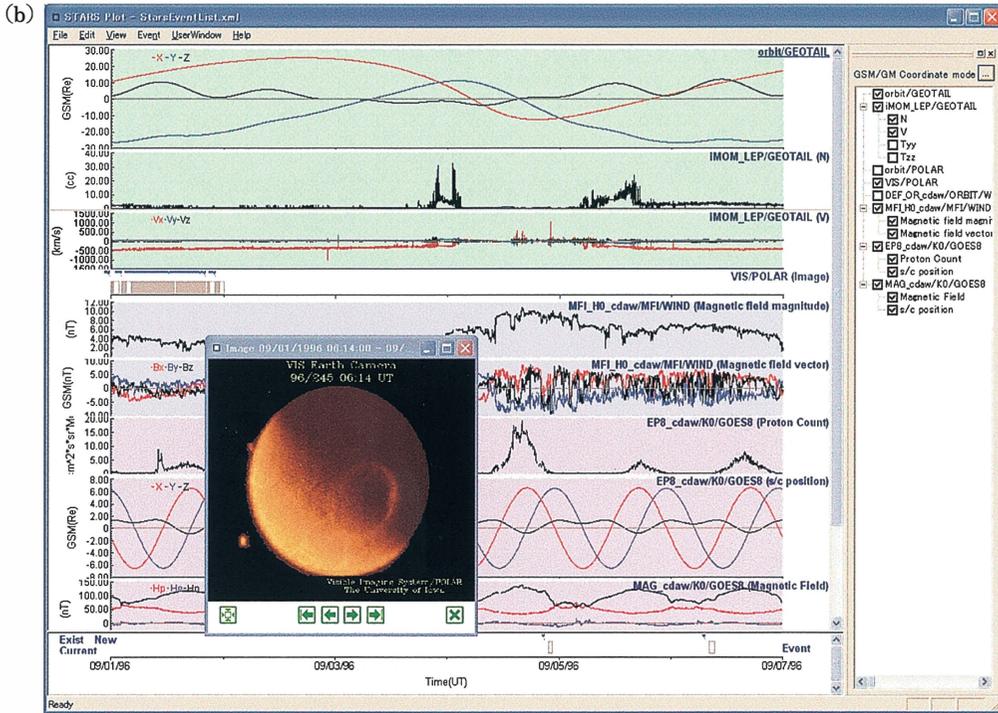
Fig. 1. The network configuration of the STARS application, STARS meta-database and observation data site.

(a)

Fig. 2. Dialog images of the STARS (Solar-Terrestrial data Analysis and Reference System) from 1st to 6th September in 1996. (a) Main window of the STARS. (b) A plot window of the STARS. (c) An orbit window of STARS. Any observation data is mapped on a satellite orbit.

(b)

(c)

3.3.   2-D Data plots of STARS

The panels in Fig. 2 are dialog images of the STARS.   In Fig. 2a, mission, team and data names are listed in the main dialog of the STARS.   STARS users make a choice of data and download data files from the observation data sites, which are distributed over the Internet (Fig. 1).   The directory information for the data files are supplied by the STARS meta-database.   Using the downloaded data files, the STARS makes plots as shown in Fig. 2b and c.

Figure 2b shows a plot of spacecraft and ground-based observations from 1st to 6th September in 1996.   This type of 2-D plot gives us easy understandings of relationship between observation data.   However, it is not easy to recognize 3-D spatial profiles of the observation data on such 2-D plots.

The graphs in Fig. 2c are plotted using one of the plot functions of the STARS. Satellite orbits are plotted on *X-Y*, *Y-Z* and *Z-X* planes and GEOTAIL/LEP ion moment (V_x component) is mapped on the orbits.   On the STARS any observation data is able to be mapped on the orbits.   This function may help user's statistical studies: the user can easily recognize global structures of observation data over the Earth's magnetosphere.   However, since the plots are simple projections on 2-D planes, it is not easy to recognize 3-dimentional spatial profiles of the data.

It should be noted that the STARS provides data plots in GSM, GSE, GEI, GEO and SM coordinate systems.   Users can select any coordinate system for their research purposes on the STARS.

4.   Virtual Earth's Magnetosphere System (VEMS)

4.1.   Concept of VEMS

Based on the STARS, we have developed a new research environment for geo-space science; Virtual Earth's Magnetosphere System (VEMS).   The main purpose of the VEMS is to provide a new environment for the studies of geo-space.   This system enables us to carry on a variety of integrated researches which have been performed individually so far.

The VEMS is constructed based on the recent information technologies such as network database and 3-D visualizations.   User first sets start time and end time, then make a choice of datasets to be visualized.   The data files are downloaded and visualized in 4-D (3-D in space and 1-D in time).   The VEMS also provides data analysis environments. (Data analysis functions of the VEMS are not discussed in the present paper.) Global MHD simulations and modeling data are also visualized in the VEMS as long as they are expressed in real parameters in space and time.

4.2.   Design and construction of VEMS

The VEMS is a system to visualize multiple observation data and simulation data for a given period in a coordinate system.   There are many coordinate systems used in the Earth and space science.   For example, the Earth's magnetosphere is usually expressed in the coordinate system of GSM (Geocentric Solar Magnetospheric) or GSE (Geocentric Solar Ecliptic).   On the other hand, the locations of ground-based observatories are depicted in the GG (GeoGraphic) or GM (GeoMagnetic) coordinate.

Fig. 3.   The VEMS framework.   Note that symbol "*" represents a reference of Loop module, symbol "< >" represents folder and symbol "≪ ≫" represents coordinates.

Fig. 4.   The module network of the VEMS on AVS/Express.

It is unreasonable to express the observatories on the Earth in the GSE coordinate system. In the VEMS, a smaller scale coordinate system is laid on a larger one as shown in Fig. 3. Due to this hierarchical structure of coordinate systems, any observation data given in the smaller scale coordinate system is expressed in the larger coordinate system without any geometrical conversion.

After the design of the VEMS, we implemented it using a visualization tool: AVS/Express provided by KGT Inc. (AVS/Express, 2004). The AVS/Express provides users with an easy environment to build original 3-D visualization systems. As is shown in Fig. 4, the construction of system is done with combining network modules. Each module of the AVS/Express has one or more functions. A variety of functional modules are supplied. Users are able to make his/her own original modules for special purposes, too.

4.3. STARS meta-database and XML for VEMS

As is discussed in Section 3.2, there are already 140 data stored in the STARS meta-database in December 2004. In order to include a variety of observation data in the VEMS, we need to prepare a set of programs for each data; data read program, data conversion program to the VEMS framework and data visualization program. As the number of data increases, it becomes a heavy job. This is one of the reasons that the VEMS type of visualization system has not shown up.

Figure 5 shows data handling process for the STARS and the VEMS. The STARS is composed of two programs: STARSdb and STARSplot. The STARSdb downloads
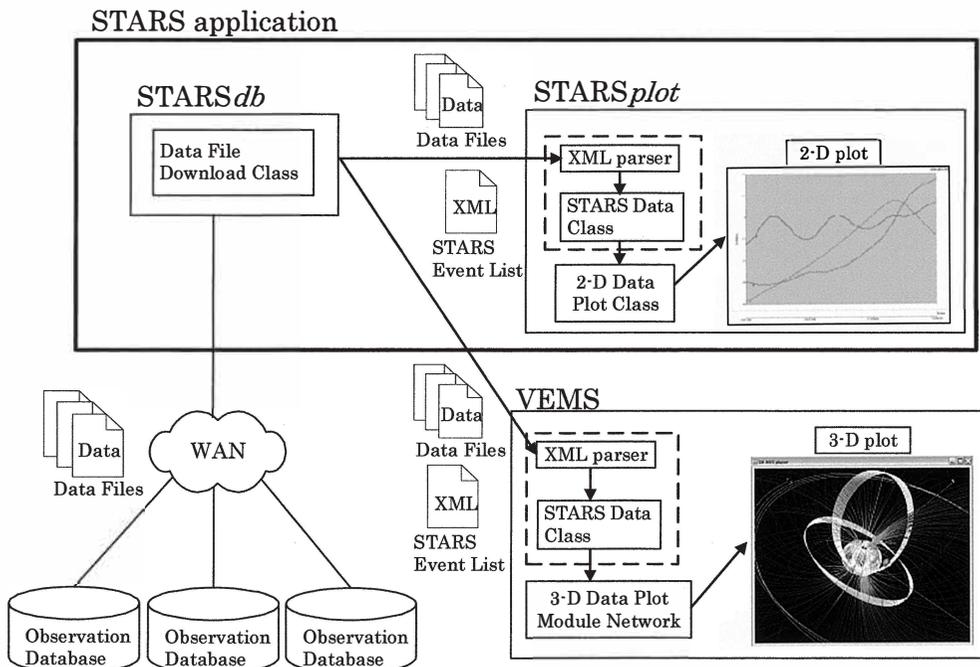

Fig. 5. VEMS cooperates with STARS.

Table 1.   A list of dataset to be visualized in the VEMS (December 2004).

Magnetic field model	Tsyganenko 2003 model
Simulation data	Global MHD simulations
Satellite observation data and ground observation data	GEOTAIL (Orbit, ion density, ion velocity and Electromagnetic field) POLAR (Orbit, Visible Imaging System data, Magnetic field) GOES-6, -7, -8, -9, -0, -12 (Orbit, Proton, Electron, Solar X-ray Fluxes and Magnetic field) WIND (Orbit and Magnetic field) AKEBONO (Orbit) ACE (Orbit and *Magnetic field*) LANL-89, -90, -91, -94, -97 (Orbit, keV proton and MeV proton) IMP8 (Orbit, Plasma and Magnetic field) IMAGE (Orbit) Interball tail (*Orbit, Magnetic field, Electron and AKR*) Interball aurora (*Orbit, Magnetic field and Electron*) SOHO (*Orbit, Proton flux and Electron flux*) Cluster (*Orbit, Electromagnetic field in the equatorial and Electron*) FAST (*Orbit, Electromagnetic field on polar, ion and Electron*) Equator-S (*Orbit, Electromagnetic field in the equator and Electron*) Ground Geomagnetic Field Data Along the 210 degree Magnetic Meridian: (position coordinates of station and geomagnetic field)

(*Italic character: data list scheduled to be included*)

data files for the periods set by users.   The list of downloaded data files are described as an XML file named STARS Event List.   The XML parser program in the STARSplot resolves the STARS Event List to bring data files from the STARSdb to the STARSplot. To read data files and convert them into the STARS data format, the STARS project prepared a data class named STARS Data Class.   The STARS Data Class defines schemata for several types of data.   This class encapsulates data files to users: users simply get a data stored in a data format regulated by the STARS data schemata.

For the construction of the VEMS, we make full use of the STARS.   As shown in Fig. 5, we replicate the XML parser and STARS Data Class of the STARSplot to the VEMS.   For the VEMS, we simply make as many AVS modules for 3-D visualization as is given by the STARS Data Class (Fig. 5).   Table 1 shows a list of datasets which are ready for visualizations on the VEMS.

5.   Application of VEMS

5.1.   *2-D plot via STARS and 4-D visualization via VEMS*

Figure 6a is a 2-D plot via STARS from 0000 UT on 1st September to 0000 UT on 7th September in 1996.   There are 5 spacecraft orbits and magnetic fields observed by them.   Ground-based magnetogram data are also shown at the bottom of the plot.

Figure 6b is its 4-D visualization (3-D in space and 1-D in time).   Spacecraft are depicted as spheres.   The color of each sphere shows one scalar data and arrows show vector data.   There are two arrows at each spacecraft.   Bold arrows represent magnetic fields given by Tsyganenko model, while thin arrows for observed magnetic fields.
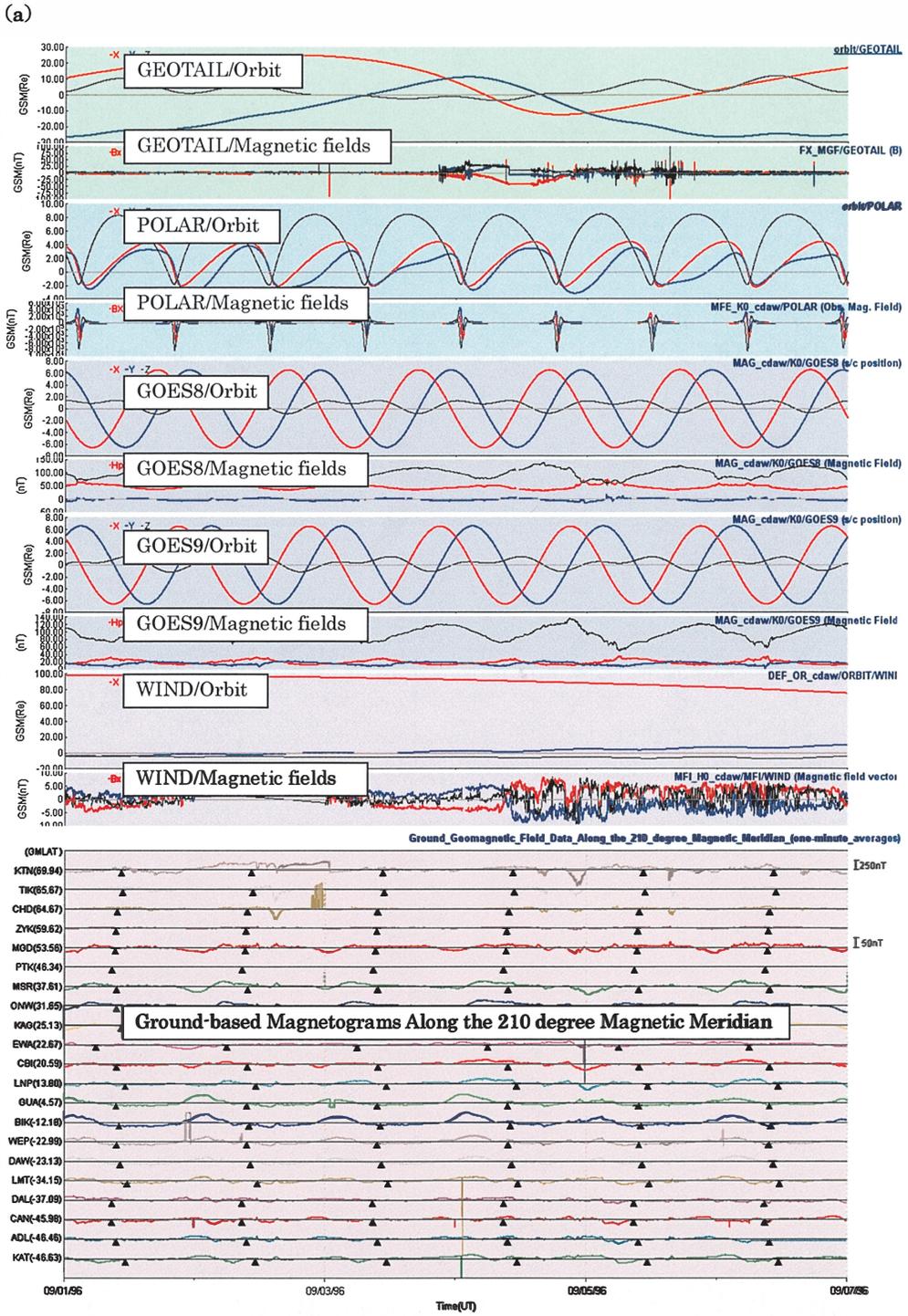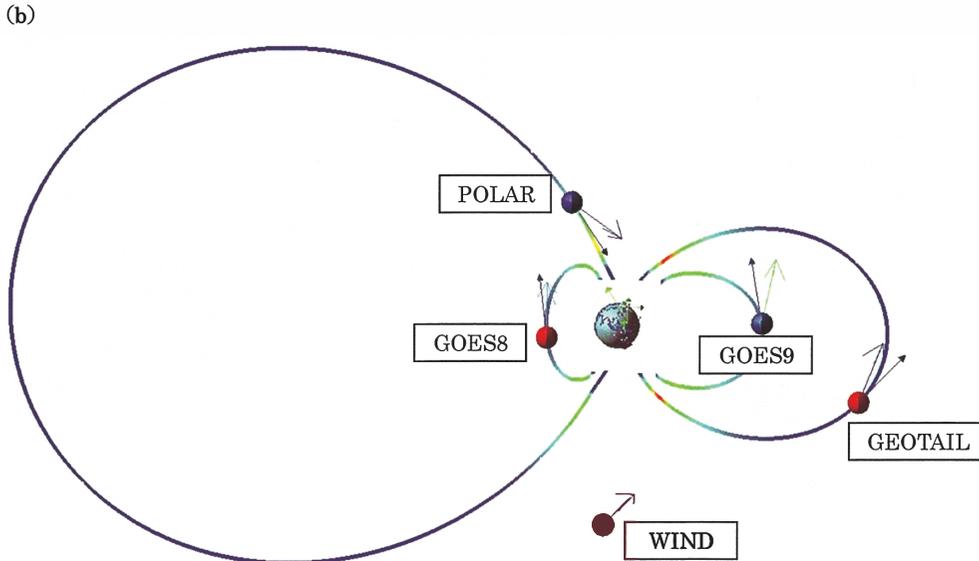
(a)

Fig. 6a.

(b)

Fig. 6. *Traditional 2-D and present 3-D visualization of satellite orbits and observation data from 1st to 6th September in 1996: (a) Traditional 2-D plot by the STARS. (b) 3-D visualization of observation data by the VEMS. A magnetic field lines are given by Tsyganenko model 2003. Bold arrows represent magnetic fields given by Tsyganenko 2003 model, while thin arrows are observed magnetic fields. The coordinate system is GSM.*

The magnetic field lines which go through spacecraft are drawn based on Tsyganenko 2003 model. The magnetic field lines move with spacecraft, thus the footpoints of magnetic field line in the vicinity of the spacecraft are visible. This may help our studies on relationship between spacecraft observation and ground-based observation such as aurora activities or magnetograms (Yumoto *et al.*, 1996).

One may find arrows on the Earth if he/she carefully take a look of Fig. 6b. These correspond to magnetogram data from Fig. 6a. Time-dependent sequences from the changes in the solar wind to the fluctuations of the Earth magnetic field are comprehensive if one uses the VEMS replay mode.

5.2. Combination of observation and simulation on VEMS

Figure 7 is an example of the VEMS from 0816 to 0935 UT on 6th September in 1996, in which observation data and simulation data are visualized in 3-D space and 1-D time. In Table 2 a list of data in Fig. 7 is shown. Figure 7 depicts a screen shot of the VEMS at 0829 UT. The positions of multiple satellites (POLAR, AKEBONO, WIND and GOES) are expressed in 3-D sphere, thus relative positions between satellites are visible. It should be noted that one can change his/her viewpoints in any direction or walk through regions in the magnetosphere.

One scalar data and one or more vector data *via* spacecraft are able to be visualized on the VEMS. In Fig. 7 the color on each sphere shows one scalar data, such as plasma density, observed by the satellite. Note that any scalar data, even one component of
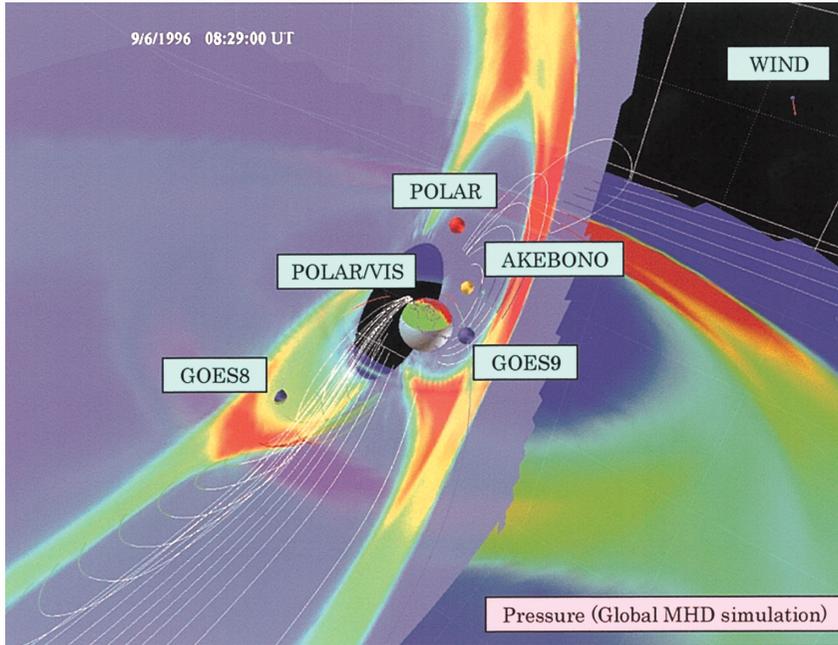
Fig. 7.   *Global MHD simulation and satellite observations.   Only the magnetic field lines which pass along the X-axis are extracted.   Pressure (Global MHD simulation) is expressed as a cross section.   The coordinate system is GSM.*

Table 2.   *Global MHD simulation and satellite observations.   The visualized period is from 09/06/1996 0816 UT to 09/06/1996 0935 UT.*

Global MHD simulation data	Magnetic field: streamline Pressure: cross section
Observation data	GOES8: Orbit, Magnetic field and Proton count GOES9: Orbit, Magnetic field and Proton count GEOTAIL: Orbit and Magnetic field POLAR: Orbit WIND: Orbit and Solar wind AKEBONO: Orbit

vector or one channel data of multi-channel observation, is able to be expressed in color. The arrow at each sphere shows an vector data like magnetic fields.   Since the VEMS provides time-dependent visualization, the color and vector changes as time goes on. On the Earth, ground-based magnetogram data (not shown in Fig. 7) or aurora image data are also depicted (Murata *et al.*, 2004).

On the VEMS, in addition to the observation data, global MHD simulation data are also visualized in 4-D format as long as the simulation is performed with real parameters.   In Fig. 7 plasma pressure is shown in color contours.   The AVS/Express pro-

vides a variety of 3-D visualization. The plasma pressure contours are given on two-planes: the *X-Y* plane and the *X-Z* plane in GSM coordinates, respectively. If one carefully see, he/she may find that the GOES 8 spacecraft is on both planes. One can directly compare GOES8 observation data (scalar or vector) with global MHD simulation results. These planes move with the satellite so that this direct comparison is possible at any moment.

5.3. *Magnetic field models on VEMS*

Instead of global MHD simulations, magnetic filed modeling data in 4-D format are also visualized on the VEMS. Figure 8 is a long durational 3-D visualized data of satellite orbits from 0000 UT on 1st September 1996 to 0000 UT on 1st October 1996 with magnetic filed lines given by Tsyganenko 2003 model (Tsyganenko, 2002). Table
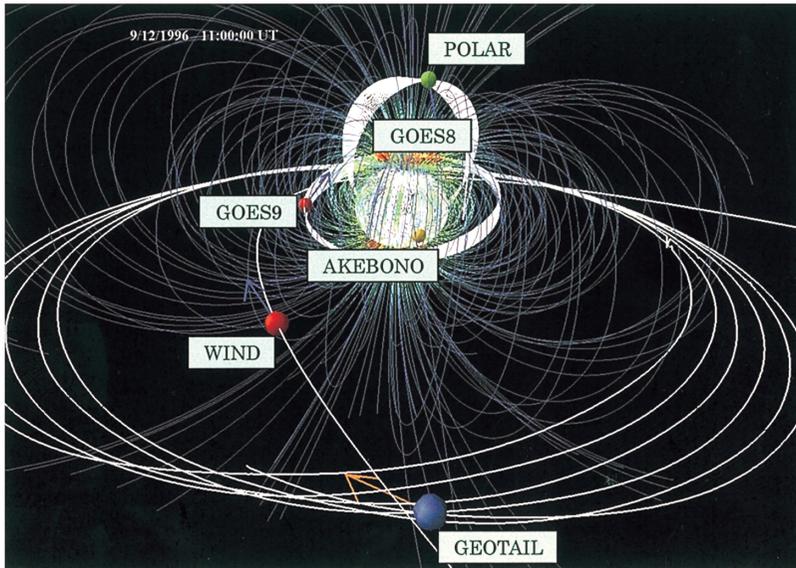

Fig. 8. *Satellite orbits and the Earth's magnetic field lines which go through the satellites. The magnetic fields are given by Tsyganenko 2003 model.*

Table 3. *Magnetic field model and satellite observations. The visualized period is from 09/01/1996 to 10/01/1996.*

Tsyganenko 2003 model	Magnetic field: streamline
Observation data	GOES8: Orbit, Magnetic field and Proton count GOES9: Orbit, Magnetic field and Proton count GEOTAIL: Orbit and Ion moment POLAR: Orbit and Magnetic field WIND: Orbit and Solar wind AKEBONO: Orbit

3 shows a list of visualization data in Fig. 8. Using the replay mode of the AVS/ Express, these satellites move along with the orbits and the model magnetic filed lines follow them. (Note that the Tsyganenko model is a time-dependent model.) This view looks simple, but helps researchers or nonspecialists to understand the positions of spacecraft in the Earth's magnetosphere.

6.   Summary and discussions

Taking into account the backgrounds of geo-space science discussed in Sections 2.1 and 2.2, we conclude that a new research environment is required in order to achieve break-through results. For the development of the researches, we need to make full use of up-to-date information technologies (IT). In the present paper, we propose a new 4-D visualization system, Virtual Earth's Magnetosphere System (VEMS). The basic concept of the VEMS is to reproduce the past Earth's magnetosphere for given period virtually in personal computers. We gather (download) satellite and ground-based observation data public on the Internet, then drop them into the VEMS. The VEMS visualizes these data in 4-dimentional format (3-D in space and 1-D in time).

The VEMS also visualizes 3-D computer simulation results or magnetic field models (*e.g.*, Tsyganenko, 2002) in the same framework with observations if the simulation is performed based on real parameters. In this case, direct comparison between observations and simulations are possible. The direct comparison helps the data interpretation by allowing researchers to put the data into a global context and allows the modellers to directly compare the results to data within the entire system. This kind of research environment has a potential to lead to data assimilations in the future. Nevertheless, it requires the helps of adequate filters, such as Kalman filter.

After the basic design, we implemented the VEMS using visualization software, AVS/Express (AVS/Express, 2004). The VEMS provides us with several visualization and analysis environments, such as re-scaling, rotation, draw of stream lines, particle trace, orthogonal slice, iso-surface and others with help of the AVS functional modules. We can handle and analyze the Earth's magnetosphere in our computers from our own viewpoints.

The VEMS does not require special computer, therefore everyone can install it on his/her personal computer (Windows PC). Generally, it is not easy for nonspecialists to search and download observation data files. In case of the VEMS, downloads of data files are supported by the STARS (Solar-Terrestrial data Analysis and Reference System), which has been developed at the Center for Information Technology, Ehime University (Murata, 2003). The operation of the STARS is not difficult: even high school students can easily download and visualize data. Consequently, the VEMS is a powerful tool. This implies that the VEMS can be used for outreach activities and educations.

It should be noted that the VEMS works on a virtual reality system. We installed the VEMS on PVR (Portable VR, 2004) which is a low-price virtual reality system (Fig. 9). Using the VEMS on the PVR, we could obtain an immersive experience of the Earth's magnetosphere: it was as if we could see the Earth and magnetosphere from the space (Watari *et al.*, 2003). Not only the immersive experience, but the VR system
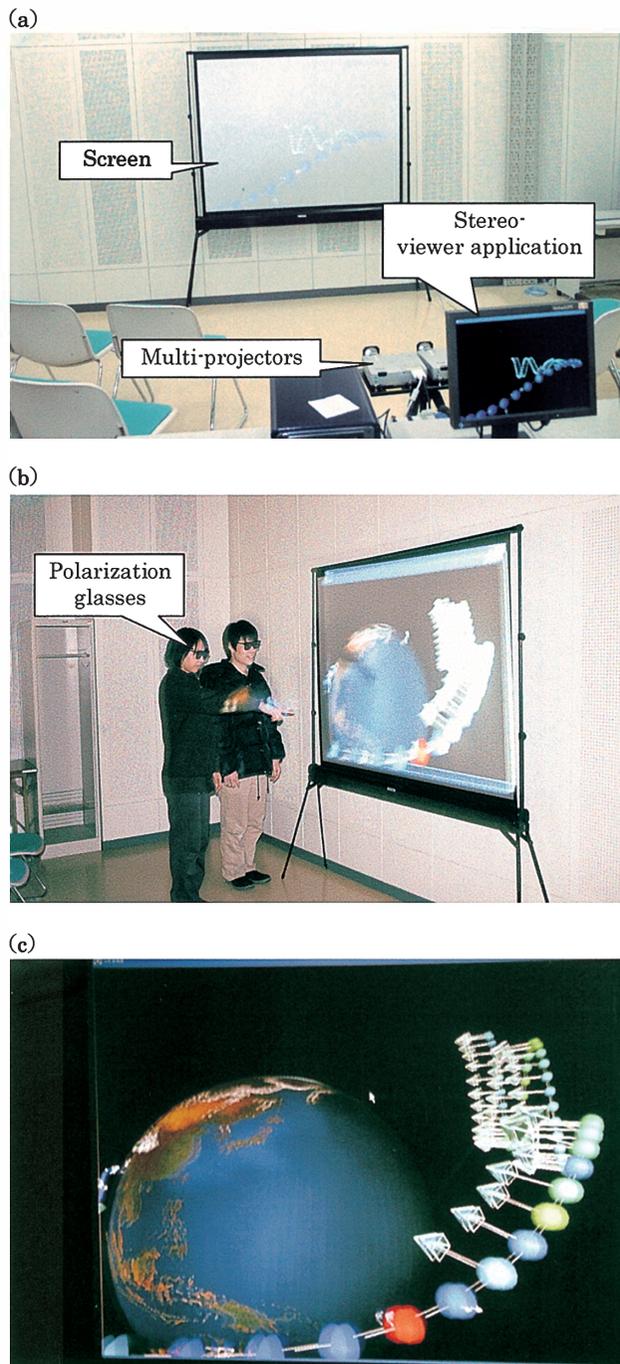
(a)

Screen

Stereo-viewer application

Multi-projectors

(b)

Polarization glasses

(c)

Fig. 9.   (a) and (b) A portable virtual reality system (Portable VR, 2004) at the Center for Information Technology, Ehime University.   (c) VEMS on PVR.

gives us more important chance to analyze the 3-D data.   For example, the magnetic field lines around a plasmoid or flux rope are complicated (Winglee *et al*., 1998), in general.   When we took a VR view of the spiral magnetic field lines around a magnetic flux rope on the PVR, we could successfully find a structure of the 3-D configurations of the magnetic field lines (Matsuoka *et al*., 2004).   This analysis is hard to be done on the traditional 3-D visualized view on the AVS.

Acknowledgments

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