DEVELOPMENT OF GEOSPACE ENVIRONMENT SIMULATOR

Hideyuki Usui
Research Institute for Sustainable Humanosphere, Kyoto University,
Gokasho Uji, Kyoto 611-0011, Japan
Phone & Fax : +81-774-38-3817
E-mail: usui@kurasc.kyoto-u.ac.jp

M. Okada
National Institute of Polar Research, Itabashi, Tokyo, 173-8515, Japan

Y. Omura
RISH Kyoto University, Uji, Kyoto 611-0011, Japan

GES Project team

Abstract

In the space development and utilization, it is very important to understand the interactions between spacecraft/structures and space plasma environment as well as the natural phenomena occurring in space plasma. In order to evaluate the spacecraft-plasma interactions quantitatively to contribute to the progress of space utilization and space technology, we aim to develop a proto model of Geospace environment simulator (GES) by making the most use of the conventional full Particle-In-Cell (PIC) plasma simulations. For the development of GES, we have been using the Earth simulator which is one of the fastest supercomputer in the world. GES can be regarded as a numerical chamber in which we can virtually perform space experiments and analyze the temporal and spatial evolution of spacecraft-plasma interactions. GES will be able to provide fundamental data regarding various engineering aspects such as the electrostatic charging and electromagnetic interference of spacecraft immersed in space plasmas, which will be useful and important information in determining designs and detailed specifications of spacecraft and space systems.

Introduction

The Solar Terrestrial Energy Program (STEP) had been undertaken since 1990 for six years. The STEP Results, Applications, and Modeling Phase (S-RAMP) have been following STEP since 1998. The successful cooperation of the International Solar Terrestrial Program (ISTP) projects had yielded various space data simultaneously observed with much higher resolution than those of the previous missions. In parallel to these intensive observations with spacecraft, owing to exponential advance in computer technology, numerical simulation has progressed as a powerful tool for the detailed study of space plasma phenomena observed with spacecraft. Collaborative simulation researches with the space plasma observation have been greatly successive. Furthermore, simulations have potential possibility to predict plasma processes which have not been observed yet because of insufficient spatial and temporal resolution of science instruments onboard spacecraft. In this aspect, space simulations are also important in planning future spacecraft observation in terms of resolution of science data and spacecraft orbit.

Space weather research has been recently highlighted in the community of the Solar-Terrestrial Physics (STP). In the space weather research, each linear/nonlinear process occurring in space plasma as well as its interrelation has been more quantitatively and intensively analyzed. Various plasma phenomena observed so far are also to be evaluated quantitatively from a view point of direct or indirect influences given by the variation of solar activities. By taking an account of the significant scientific achievement brought by space simulations in the last two decades, it is easily recognized that computer simulations can keep contributing to the understanding of each physical process residing in the plasma phenomena in the space weather research.

Meanwhile, space development has been rapidly increasing as shown in the construction of International Space Station (ISS), In such a situation, a strong demand should arise regarding the understanding the space environment around space structure, which are very important issues associated with the human activities in space. We believe that space simulations should start the contribution to the understanding of various types of environmental disturbances caused in the process of spacecraft interaction with space plasma by the feedback of the knowledge of plasma physics previously learned from the analysis of natural plasma phenomena. Basic spacecraft-environment interactions are described in [1] and [2].

In order to evaluate the spacecraft-plasma interactions quantitatively to contribute to the progress of space utilization and space technology, we aim to develop a proto model of Geospace environment simulator (GES) by making the most use of the conventional full Particle-In-Cell (PIC) plasma simulations.

Geospace Environment Simulator (GES)

Figure 1 show the basic concept of Geospace Environment Simulator called GES. We have two major core engines for numerical simulations. One is electromagnetic (EM) simulator which enables us to investigate the electromagnetic interaction in association with the spacecraft-plasma environment. One of the research targets is the analysis of electric field antenna characteristics in space plasma environment such as photoemission and plasma sheath. In in-situ spacecraft observation of plasma waves, we need to know the quantitative antenna characteristics in order to calibrate the wave data. The antenna analysis is needed for the antenna design for the future missions. The EM simulator can handle the electromagnetic field variation as well as plasma kinetic effects with full PIC model. The other numerical engine is electrostatic (ES) simulator with which we can examine the spacecraft charging and associated plasma response, active plasma emission and its plume interaction. The GES team can collaborate with the MUSCAT project, which has been approved by JAXA to develop as a numerical tool for the spacecraft charging, by making use of this ES simulator. The two engines are basically full PIC model bases. The spacecraft configuration can be modeled either by Cartesian coordinate grids or unstructured grids. Unlike the other numerical tools for the spacecraft charging, GES can solve the time-dependent and transient plasma environment self-consistently as well as the steady state. Other effects such as photoelectron emission and secondary electrons are planned to be included. Regarding to the background plasma data, we will utilize the space plasma data obtained by the space weather modeling, in-situ satellite observations as well as global MHD simulations.

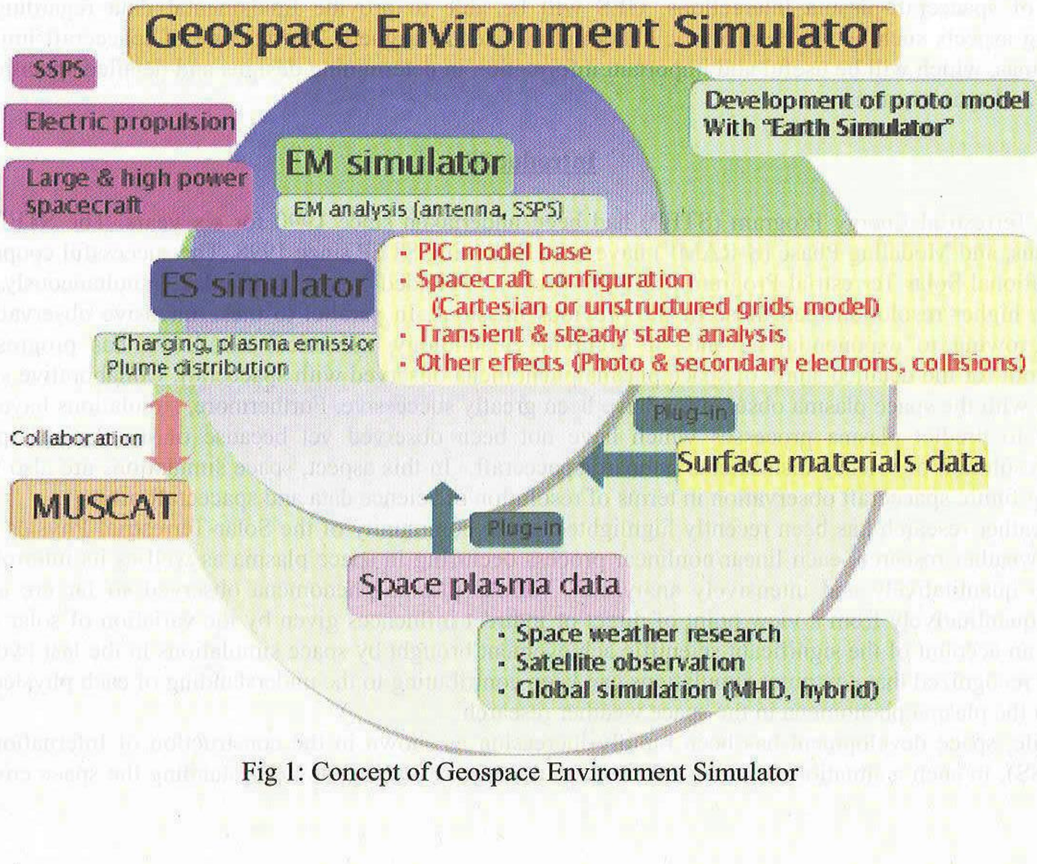

Fig 1: Concept of Geospace Environment Simulator

Development of GES with the Earth Simulator

The Earth simulator is one of the fastest supaercomputer in the world. It consists of 640 nodes of vector-type supercomputer. Each node has 16GB main memory shared with 8 vector processors. The total size of the main memory is 10 TB and the maximum performance is 40TFLOPS. The development of proto model of GES has been approved for the usage of the Earth simulator. However, each application on the Earth simulator is required to achieve the maximum optimization for vecterization and parallelization because of the efficient performance of simulations. We started to develop and tune the core engine of the EM simulator called NuSPACE which contains the particle pusher and EM field solver with domain deponposition. With the intensive code tuning approximately for two years, we succeeded in achieving the maximum optimization of NuSPACE. The vecterization and parallelization efficiencies are almost 100 %.

Approximately with 500 nodes at the Earth simulator, we can create 8 cubic nodes simulation region as shown in Fig. 2. Since the grid size should be comparable to the local Debye length in PIC simulations, we can have approximately 200 cubic grid region in one node when we have about 100 particles per cell. This implies that approximately 1000 times Debye length volume regions can be treated with the use of the Earth simulator. To model complex spacecraft geometories in the center node, we plan to use unstructured grid system as shown in Fig. 3.

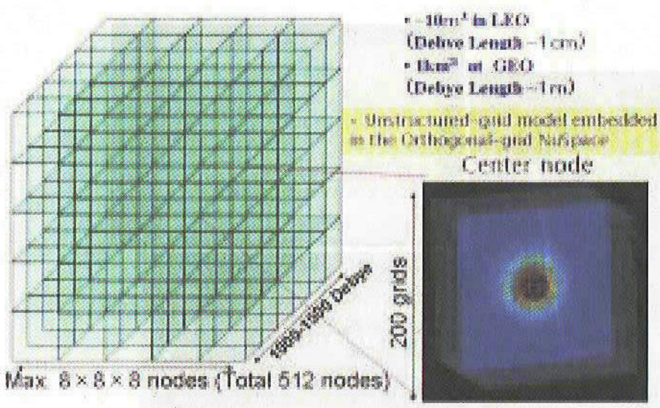

Fig. 2 Domain decomposition for NuSPACE code for the Earth simulator

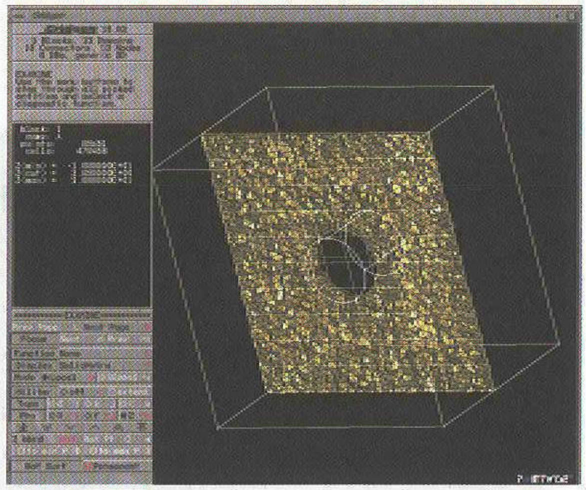

Fig 3. Unstructured grid modeling for complex spacecraft configuration

Research Targets of GES

The GES is a kind of numerical plasma chamber and currently we are considering the applications as shown in Fig. 4 in terms of spacecraft-plasma interactions. As mentioned, the antenna characteristics in space plasma environment such as photoemission and plasma sheath are very important in the data calibration as well as the antenna design for future missions. Particularly, we are interested in the effects of photoemission on the antenna characteristics. Space Solar Power System (SSPS) is another good example of space applications. In SPS, solar energy is collected by a large number of solar cells attached to the satellite and is transmitted to a ground station or to another satellite by using microwave. To study the feasibility and the implications of SPS, we started a research program of the microwave power transmission (MPT) in the 80's by conducting rocket and ground experiments. The rocket experiments showed that electrostatic waves were excited around the local plasma frequency in association with the microwave emission. Corresponding computer simulations revealed that the electrostatic wave generation is due to the stimulated Ramann scattering type of the nonlinear three-wave coupling process in the ionospheric plasma [3]. The simulations also predict the electron heating associated with the ES wave excitation [4]. These simulation results are very interesting and important not only from the plasma physics point of view but also from the engineering side because they are useful in evaluating the threshold of the microwave power transmitted from SPS to the ground. In this aspect, space simulation can be a powerful tool to obtain useful engineering information regarding how to minimize the undesirable effects to the space environment and to maximize the efficiency of power transmission in SPS.

In the future space activities, large-scale space structures with high voltage and thruster firings with electric propulsion using ion engine will be commonly utilized. From a microscopic point of view, spacecraft interactions with the contaminated plasma environment which consists of exhausted plasma plume, neutral gas, and ambient plasma are to be quantitatively investigated. Particularly, to avoid the discharge, the evaluation of the spacecraft surface charging is very important as a consequent of electrostatic interactions among plasma plume, spacecraft surface including solar paddle, and the ambient plasma.

In addition, the global influence of exhausted products from ion engine on the plasmasphere, magnetosphere, and ionosphere will become a serious environmental problem in the plasmasphere, magnetosphere, and ionosphere. For instance, it is reported by [5] and [6] that transport of SPS with 10^7kg needs Argon propellant of approximately 10^6kg which is almost equal to the total amount of ions consisting of the plasmasphere and ionosphere. Approximately 80 % of the total propellant will be exhausted in the plasmasphere within 4 Re where Re denotes the Earth radius. Since the exhaust products are heavy ions, the kinetic energy of the exhausted ions can well overwhelm the thermal energy of the ambient plasma. This situation implies that the operation of electric propulsion with heavy ions may cause the accumulation of huge mass and energy by exhausted products in the plasmasphere.

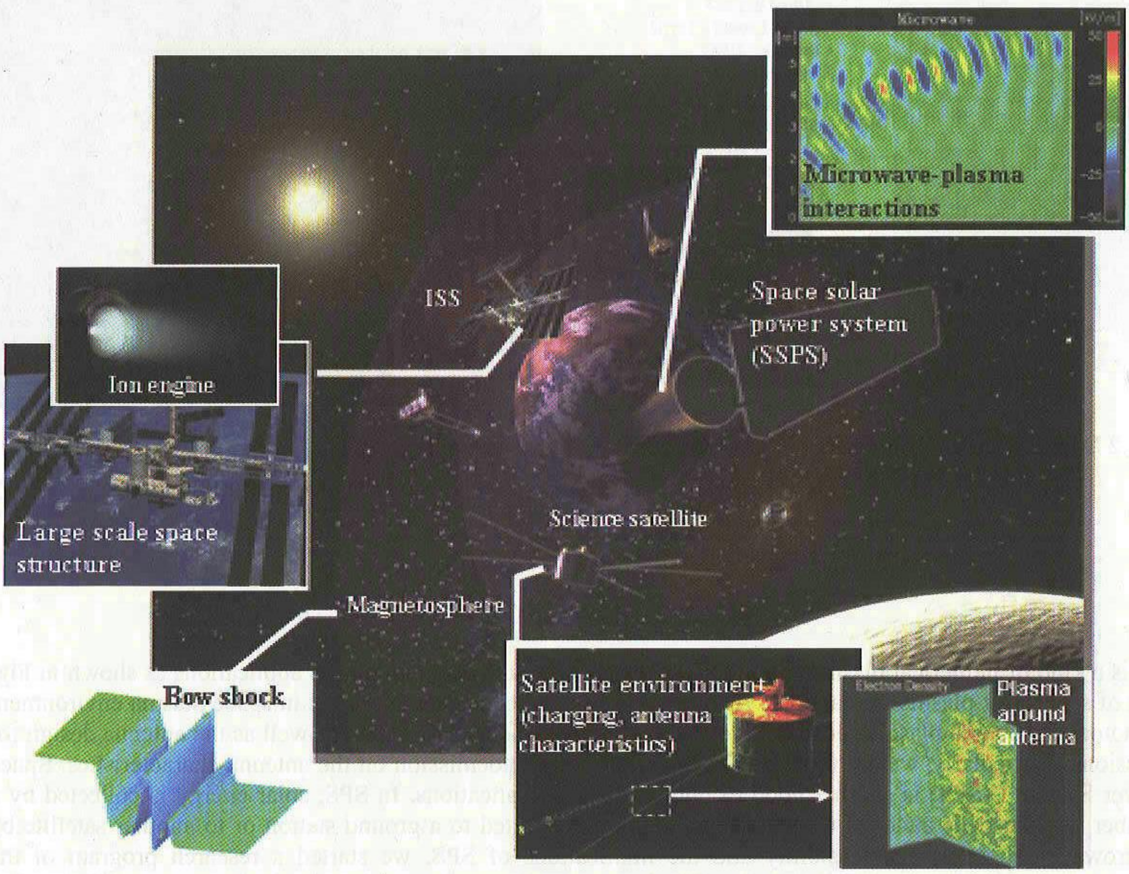

Fig 4. Research targets for GES

Conclusions

Space plasma simulations have been greatly contributing to the quantitative understanding of various natural phenomena occurring in the solar-terrestrial environment. Meanwhile, space development has been rapidly increasing by using a large-scale space structure such as ISS. In order to minimize the undesirable effects caused by spacecraft-environment interactions, it will be required to understand the effect of space environment on the spacecraft system or vice versa.

In order to evaluate the spacecraft-plasma interactions quantitatively, we started to develop a proto model of Geospace environment simulator (GES) which can be regarded as a numerical plasma chamber by making the most use of the conventional full PIC plasma simulations. GES will provide fundamental data regarding various engineering aspects such as the electrostatic charging and electromagnetic interference of spacecraft immersed in space plasmas, which will be useful and important information in determining designs and detailed specifications of spacecraft and space systems. For the development of core engine in GES, NuSpace, we have been using the Earth simulator and successfully achieved the maximum optimization of vectorization and parallelization. To model complex geometry of spacecraft in GES, we also started to develop unstructured grid simulation code. The results on spacecraft charging obtained by GES can be also used as a cross check solution to those obtained in MUSCAT which JAXA started to develop for the spacecraft charging analysis.

Acknowledgment

This study has been carried out as a part of collaborative research of "MUSCAT" granted by JAXA. The development of GES has been performed in the research project 'Geospace Environment Simulator' of the Earth Simulator Projects of FY2004. Test computation was performed with the KDK system of Research Institute for Sustainable Humanosphere (RISH) at Kyoto University as a collaborative research project and the supercomputer system at National Institute of Polar Research (NIPR).

References

1. Hastings, D. E., A review of plasma interactions with spacecraft in low Earth orbit, *J. Geophys. Res., 100, A8*, 14457-14483, 1995.

2. Hastings, D. E., and H. Garrett, Spacecraft-environment interactions, Cambridge university press, 1996.

3. Matsumoto, H., Y. Hashino, H. Yashiro, N. Shinohara, and Y. Omura, Computer Simulation on Nonlinear Interaction of Intense Microwave with Space Plasmas, *Electronics and Communications in Japan, Part3, 78}* 89, 1995.

4. Usui, H., H. Matsumoto, R. Gendrin, and T. Nishikawa, Numerical simulations of a three-wave coupling occurring in the ionospheric plasma, *Nonlinear Processes in Geophysics, Vol.9 No. 1*, 1-10, 2002.

5. Chiu, Y. T., Fate of Argon ion injection in the magnetosphere, *AIAA paper 8*0-0891, 1980.

6. Curtis, S. A. and Grebowsky, J. M., Energetic ion beam magnetosphere injection and solar power satellite transport, *Journal of Geophysical Research, 85, A4,* 1729-1735, 1980.