MULTI-UTILITY SPACECRAFT CHARGING ANALYSIS TOOL (MUSCAT): DEVELOPMENT OVERVIEW

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Abstract

Since the failure of ADEOS-II, charging of satellites in polar orbit has become a serious issue. The Japan Aerospace Exploration Agency has decided to develop a computational tool that can calculate charging status of a polar orbiting satellite jointly with Kyushu Institute of Technology. The simulation code is a combination of a particle-in-cell method and a particle tracking method and can be used not only for a polar satellite but also for a GEO satellite or a low inclination LEO satellite. The aim of the simulation code is to give satellite designers chances to identify the charging hazard in the satellite design phase with user-friendly interface. The development of software, named Multi-utility Spacecraft Charging Analysis Tool (MUSCAT), started in December, 2004. Overview of development plan and current status of the simulation code will be presented.

Introduction

At present, increasing activities in space requires large amount of electric power. For efficient power management on spacecrafts, systems that generate and transmit electric power at high voltage are increasingly employed. When generated voltage is increased to lower the power loss, however, interaction between the spacecraft and the ambient space plasma is increased and damage the spacecraft sometimes for a complete loss. As an example, Japan Aerospace Exploration Agency (JAXA) determined that the total loss of ADEOS-II, a polar Earth orbit (PEO) satellite with bus voltage of fifty volt, attributed to interaction between the plasma environment and its multi layer insulation (MLI) around wire harness. During investigation process of the loss of ADEOS-II, it was revealed that charging of a polar satellite could cause serious failure including total loss. At the same time, the fact that there was no technology to calculate charging of a polar orbiting satellite in Japan was recognized.

In order to prevent power system failure due to charging like what occurred on ADEOS-II, quantitative analysis from the viewpoint of charging-arcing issue from the early stage of satellite designing phase is necessary. Electric potential of satellite body with respect to ambient plasma and differential voltage of each surface component with respect to the satellite body potential are the most important elements to consider charging-arcing problems. Charging analysis from the satellite design phase is necessary to ensure safe operations for earth observation satellites in PEO.

Satellites in PEO are exposed to unique plasma environment including low energy (0.1~0.2 eV) ionospheric plasma and high-energy auroral zone particles. In LEO with a low inclination angle low energy particles are dominant. In GEO, on the other hand, high-energy particles are dominant. Therefore, an analyzing tool developed for PEO can be used both for LEO and GEO with minor modification. Once an analyzing tool is developed, it will be available for charging analysis of LEO spacecrafts such as science satellites or ISS, and for large telecommunication satellites or broadcasting satellites such as ETS-VIII.

At present, JAXA uses NASACAP/GEO and NASCAP/LEO, which were developed in 1970's, as spacecraft charging analyzing tool [2]~[4]. Nowadays, they are de facto standard in the world. To analyze charging status of a polar satellite [5], POLAR developed in 1980's is necessary. NASCAP/GEO, NASCAP/LEO and POLAR were all developed with technologies in 70's and 80's and their usability like user interface are not so good and satellite modeling function are limited. Although, a new version of NASCAP, NASCAP-2k, has been developed in the U.S for GEO, LEO and PEO, it is not available in Japan because of export restriction. In Europe, software called SPIS is under development since 2002 as an open-sourced software. It is, however, not easy to use for a satellite designer with little knowledge about computer language, especially JAVA.

In Japan, Space Plasma Simulation Group promotes "Geospace Environment Simulator (GES)" project using the Earth Simulator, one of the fastest computer at present in the world. As a component of GES, a computer code for simulating plasma environment surrounding a satellite is under construction. The code includes elemental physical processes of space plasma and interaction between space plasma and spacecraft so that it can be used not only for scientific computation but also for practical usage by utilizing high performance of the Earth Simulator. As GES uses Particle-in-Cell (PIC) method for computation of environment around spacecraft, however, it requires long computation time even for the Earth Simulator [6]. Even GES needs long computation time to simulate the whole spacecraft charging processes with the time scale of the order of seconds or minutes. Therefore, although GES is very powerful, it is not useful for easy use like parametric runs in spacecraft designing phase (Table 1).

Objectives

To solve the previous situation, JAXA decided to develop its own charging analysis tool that can calculate charging status of a polar orbiting satellite jointly with Kyushu Institute of Technology (KIT). The numerical tool is named as Multi-Utility Spacecraft Charging Analysis Tool (MUSCAT), so that it can be used not only for PEO but also for GEO and LEO. It will be used to evaluate the risk of charging in spacecraft design phase, to determine appropriate parameter settings of ground tests by calculating

Table 1 Comparison between MUSCAT and GES

	MUSCAT	GES
Computer	Workstation	Super Computer
Main Algolism		
Sheath	PIC	PIC
Inflow Current	Tracking Method	PIC
Accuracy	Approximate	Almost Exact
Computational Time		
Accurate Model	About Half a Day	Huge Amount of Time
Simplified Model	Around Ten Minutes	1Day
Usability in Degign Phase	Easy to Cut-and-Try	Required Utilization Plan

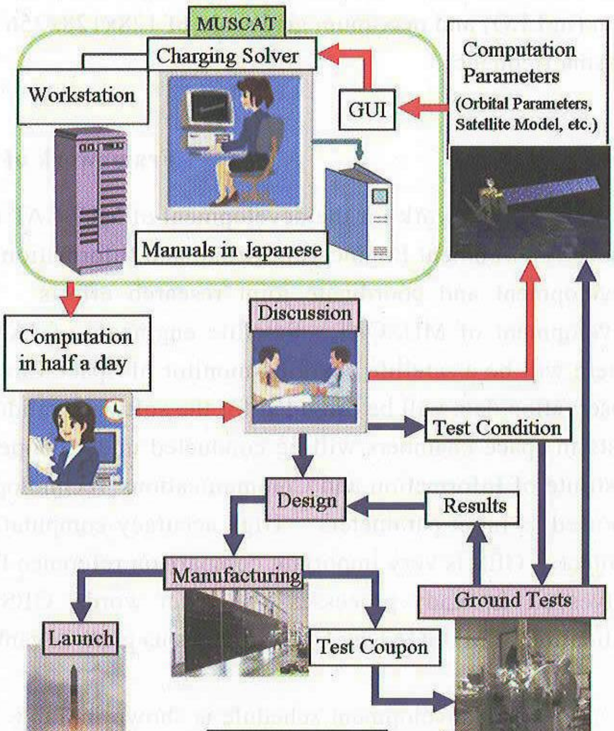

Fig.1 Role of Muscat in a spacecraft project

the worst-case charging potential, and to determine whether a given satellite failure is due to charging or not (Fig.1).

Fundamental algorithm of MUSCAT is based on a two-dimensional electrostatic solver developed by Cho et al [7]. The algorithm consists of PIC and a particle tracking method. The code will be expanded for three-dimensional analysis and added with modern computer graphical user interface (GUI). The development efforts include setting up of computer system, construction of fast numerical solver, development of user-friendly GUI to model a satellite with complex geometry and visualization of computational results and user's manuals in Japanese and English.

MUSCAT will have the following functions;

1) Input parameters for spacecrafts properties: The "spacecraft properties" includes three dimensional geometric shape of spacecraft, spacecraft attitude with solar incident angle, charging-related material properties of spacecraft surface, active emission of charged particle beam and low energy plasma.

2) Input parameters for space environment: The plasma environment includes densities, temperatures and velocities of ambient electron and ion. The environmental parameters can be chosen from calm state or the worst case such as substorm or aurora zone. Statistical analysis will be possible by running parametric runs that cover a range of environmental parameters with statistical weighting.

3) Computation of spacecraft potential and its surrounding plasma: MUSCAT will give spacecraft potential with respect to the surrounding plasma (absolute potential) and surface potential of each part with respect to the spacecraft main body (differential voltage). MUSCAT will also give the plasma distribution around a spacecraft.

4) GUI: MUSCAT enables users to input satellite and environmental parameters with GUI and provides computational results in an easy-to-understand way. The interface together with user's manual makes it possible for beginners of spacecraft charging and computer simulation to learn how to use MUSCAT with training of three days.

We aim to enable MUSCAT to conduct accurate and precise computation for a large satellite on polar orbit in half a day using commercial-type general-purpose workstation. Minimum spatial resolution of about 3cm (in LEO) and maximum grid scale of 128x128x256 are planned. The time resolution is the inverse of ion plasma frequency.

Framework of Development

Framework for the development of MUSCAT is shown in Fig.2. KIT mainly develops the software. Space Environment Engineering Group and Information Technology Center (IT Center) of JAXA supervise the development and coordinate joint research efforts. The IT Center also gives technical supports to the development of MUSCAT. Satellite engineers of JAXA will test the software and provide use-feedbacks. There will be a satellite charging monitor of Space Environment Engineering Group onboard ETS-VIII. The observation data will be provided for the software validation. To validate the computational accuracy, ground tests in space chambers will be conducted under cooperation with JAXA. We also cooperate with National Institute of Information and Communications Technology (NICT) to formulate space environment database to be used as input parameters. High accuracy computation will be also conducted as joint research with GES project. GES is very important comparison reference for MUSCAT because it includes no approximation and solves all unsteady processes. In other words, GES is a Numerical Space Chamber experiment. Code validation of MUSCAT by GES provides us great advantage for the development.

The development schedule is shown in Table 2. We started the project in November, 2004 and are going to complete in March, 2007. The first five months is the period for preparation of development. The next one year is period for basic development. Many important functions like secondary electron, back scattered electron, aurora current etc. are included in the main charging solver and GUI will be developed to model an arbitrary geometry object into the computational grids. Parallelization and tune-up of the solver code will be done as well as validation by ground experiments. As a halfway landmark, we plan to release the beta version of MUSCAT by the end of the period, March, 2006. The last one year is the period of

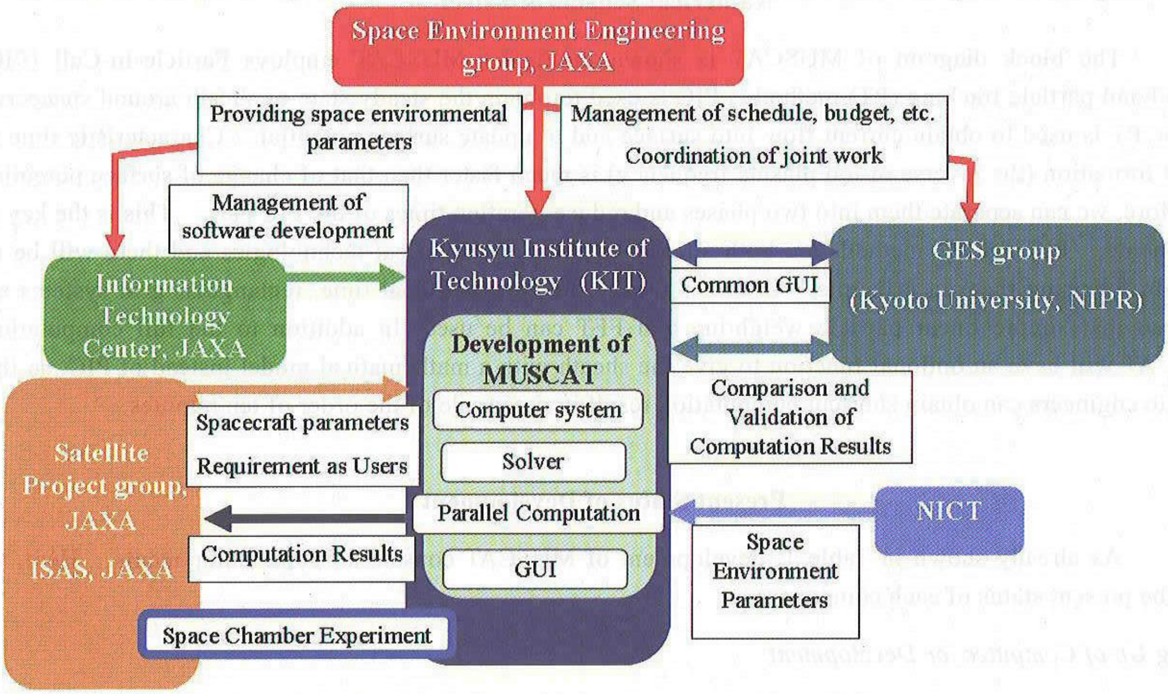

Fig.2 Framework for the development of MUSCAT

Table 2 Schedule of the development

	Nov.,2004	Release of Beta ver.	Release of Final ver.
	Apr.,2004-Mar.2005	Apr.2005-Mar.2006	Apr.2006-Mar.2007
Construction of Computer System (KIT & JAXA)	Computer System Construction	Maintenance	
Development of Solver and Tuning up (KIT)	Basic Function Development	Essential Function Development	Additional Function Development and User's Feedback
Development of GUI (KIT & Kyoto University)	Essential Function Development		Additional Function Development and User's Feedback
Material Database Building up (KIT &JAXA)	Acquisition of data		
Code validation by Vacuum Chamber Experiment (KIT & ISAS)	9th SCTC	Comparison to Langmuir probe experiment	Experiment with Satellite Mock-up
Comparison with GES (KIT & Kyoto University)	Preparation for Experiment	Comparison to Langmuir probe experiment	Comparison with simplified satellite model
Code Validation by Observation data of ETS-VIII (JAXA & KIT)		Continue after ETS-VIII launch	

modification based on user-feedbacks and advanced development. Code validation will be continued from the previous period and the final version of MUSCAT will be released by the end of the period, April 2007.

Numerical Scheme of Solver

The block diagram of MUSCAT is shown in Fig.3. MUSCAT employs Particle-In-Cell (PIC) method and particle tracking (PT) method. PIC is used to obtain the steady state of sheath around spacecraft and the PT is used to obtain current flow into surface and to update surface potential. Characteristic time of sheath formation (the inverse of ion plasma frequency) is much faster than that of change of surface potential. Therefore, we can separate them into two phases and reduce iteration times of the PIC part. This is the key of the scheme. PIC and PT methods are both already established numerical technologies and there will be no problem for using them in principle. In order to save the computational time, rectangular grid systems are used, so that simple linear particle weighting and FFT can be used. In addition to the full computation, MUSCAT will have an optional function to give the sheath with a mathematical model instead of PIC, so that satellite engineers can obtain shortcut computation result in time scale of the order of ten minutes.

Present Status of Development

As already shown in Table 1, development of MUSCAT consists of some components. Here, we describe present status of each component.

Setting Up of Computer for Development

First, a multiprocessor computer as development platform has already been installed. The Linux workstation has 8 CPUs and each CPU is 1.3 GHz 64bit Itanium II processor. The workstation is a shared memory machine with 16GB memories. Operation System is SuSE Linux and the solver part of MUSCAT is developed with Intel Fortran for Linux 8.1 and Intel C^{++} for Linux 8.1.

Development of Charging Solver

Since November 2004, we have developed basic three-dimensional solver. The solver includes basic functionalities shown in Fig.3. The current version can calculate a satellite potential with dielectric surfaces self-consistently with total charge acquired by the satellite body. We can include the effects of ambient electrons, ions, and background current simulating aurora particles. Figure 4 shows temporal variation of body potential and total charge in the body. We can see that the floating potential of the body changes as the body acquires charge. Figure 5 shows the differential voltage over spacecraft surface, where the surfaces with different color correspond to dielectric surface and others correspond to conductor surface connected to the spacecraft body. Figure 6 shows an example of ray-tracing that is necessary to include the effect of photo-electrons on

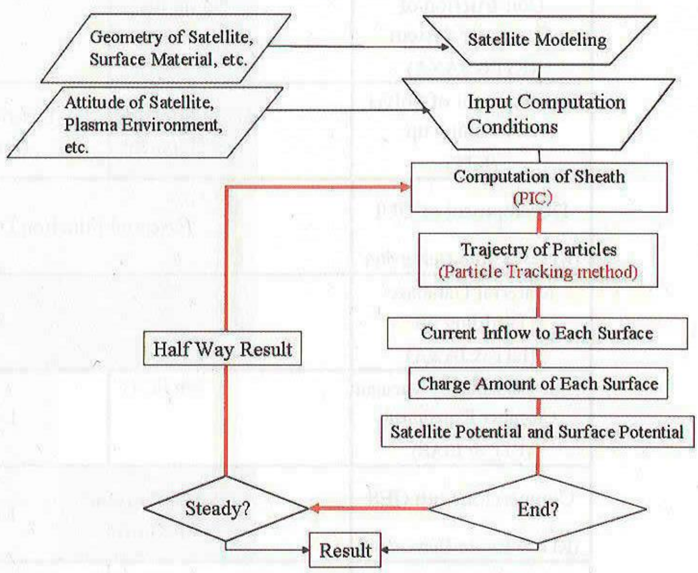

Fig.3 Schematic of algorithm

surface charging. The color contour shows intensity of sunlight. Parallelization of the solver has just started in March, 2005. Figure 7 shows improvement of particle tracking computation time by parallelization. With 8 CPUs, the computational speed has improved by 600% even if we gave just simple parallelization commands.

Graphical User Interface Development

The present GUI can build a simplified satellite model from elements of rectangular boxes and spheres in step-by-step manner (Fig. 8). In order to assist users to build a satellite model, the GUI has a function to change the viewpoint. The code can define satellite surface properties such as capacitance and generate an input file read by the charging solver and used for computation.

Experiment for Code Validation

As for the code validation experiments, we are going to construct new vacuum chamber facilities at Laboratory of Spacecraft Environmental Interaction Engineering (La SEINE) of KIT by early summer of 2005. Three vacuum chambers, for LEO, GEO and PEO respectively, will be installed in the laboratory. Preliminary tests for the electrostatic probe experiment started in March, 2005.

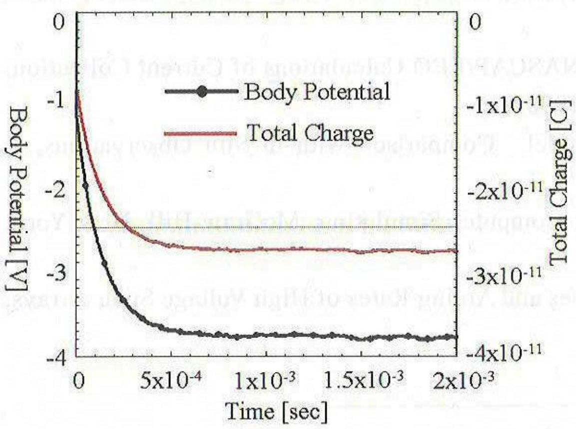

Fig.4 History of potential and total charge

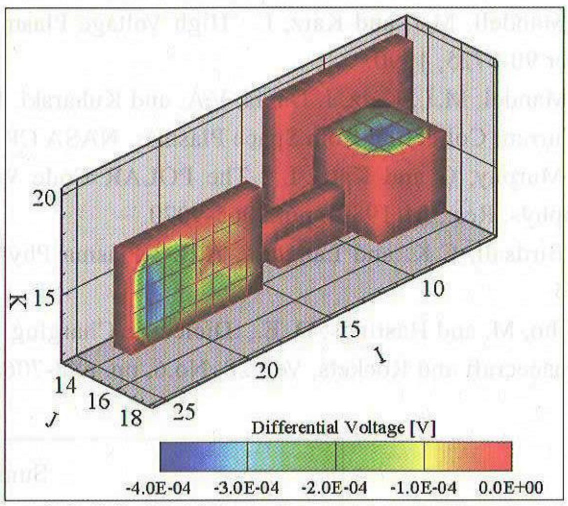

Fig.5 Differential voltage of a satellite model

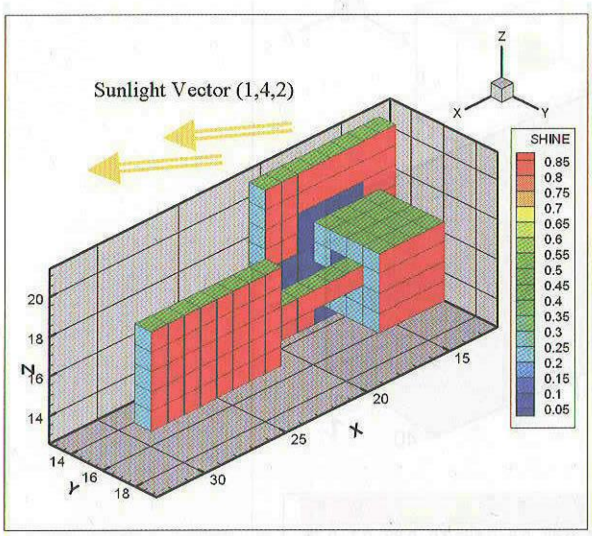

Fig.6 Example of ray tracing

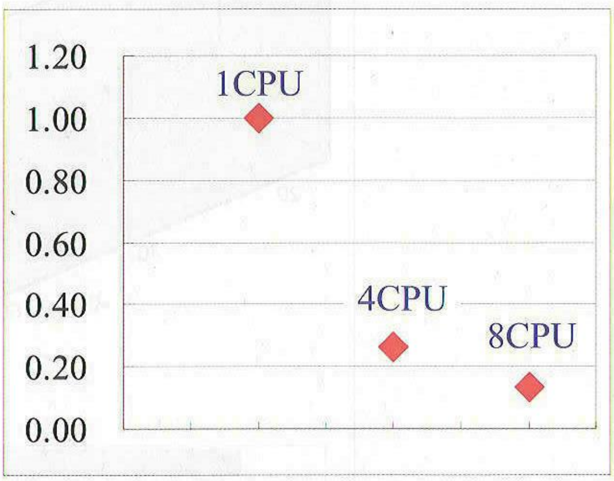

Fig.7 Speed dependence on CPU number
(For subroutine of particle tracking)

Conclusion

JAXA has decided to develop a spacecraft charging analysis tool named MUSCAT. The development is a joint work of JAXA and KIT, but it also includes collaboration with GES and NICT. The development goal of MUSCAT is to compute accurate charging status of satellite in LEO, GEO and PEO within half a day. The development started in November 2004 and will end by April 2007. Development is now in progress according to the original plan. The beta version of MUSCAT will be released by the end of March 2006 for user testing. The final version will be released by the end of April 2007.

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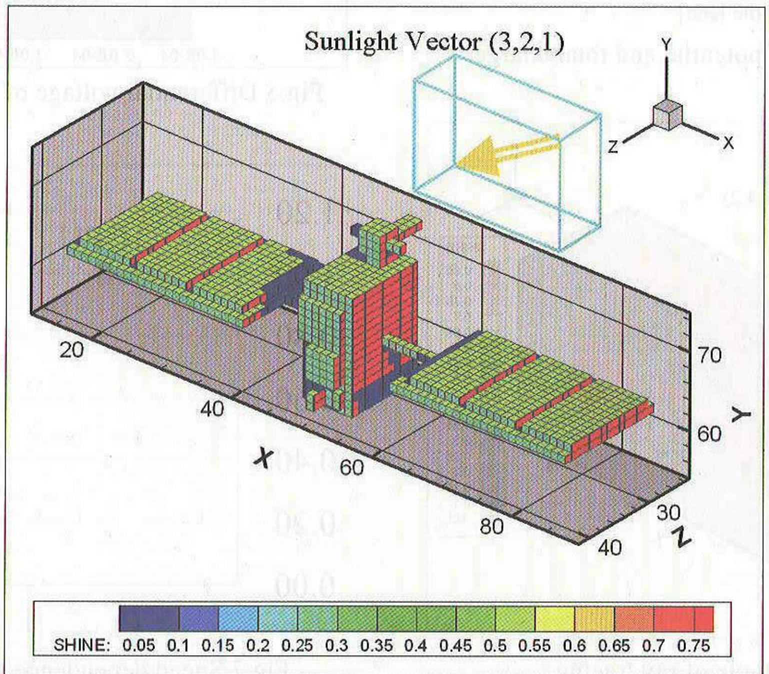

Fig.8 Ray tracing model of OICETS (100x128x64 grids)