

2-2-3 Prediction of the Plasma Environment in the Geostationary Orbit Using the Magnetosphere Simulation

NAKAMURA Masao

The geostationary orbit satellites are used for communication, broadcasting, meteorological observation, etc. and have become important social infrastructures. Since the interaction between the satellites and the plasma environment sometimes induces charging and electrostatic discharging, which cause satellite anomalies, the prediction of the plasma environment in the geostationary orbit is an important subject of space weather. We briefly describe the plasma environments inducing satellite charging and introduce the study of the prediction of the plasma environment in the geostationary orbit using the magnetosphere simulation.

Keywords

Magnetosphere simulation, Magnetospheric substorm, Geostationary orbit satellite, Satellite charging

1 Introduction

The space plasma environment surrounding the earth is known to fluctuate significantly in conjunction with a variety of activities induced on the sun's surface and sometimes causes satellite anomalies. The space plasma environment is divided into two types: one with energy of several to several hundreds of keV (kilo electron volts) that causes satellite charging due to electrostatic reaction, and one (also called the space radiation environment) with high energy of several hundreds of keV or larger that causes anomalies in semiconductor elements due to the ionization effect. About half of the satellite anomalies occurring in orbits are reportedly caused by satellite charging as described above and, together with those caused by the ionization effect as subsequently described above, about 80% is due to the space plasma environment[1][2]. This paper describes the space plasma environment that causes satellite charging. Specifically, since charging on the surface of a satel-

lite easily occurs in geostationary orbit, predicting plasma environment fluctuations in geostationary orbit is a crucial issue for space weather.

2 Geostationary orbit plasma environment and satellite charging

2.1 Space plasma environment

The sun irradiates solar wind — a supersonic stream of plasma containing a magnetic field. The plasma environment surrounding the earth fluctuates significantly due to the interaction between solar wind and the geomagnetosphere produced by the earth's intrinsic magnetic field. A portion of energy and plasma flows into the magnetosphere through the magnetopause and accumulates in the magnetotail, depending on various conditions such as solar wind density and velocity, and the magnetic field's direction and intensity. In the process of suddenly releasing the energy accumulated, plasma in the magnetotail is

transferred while being accelerated and heated to the inner magnetosphere, which includes the geostationary orbit. The phenomenon whereby energy is suddenly released called a magnetospheric substorm. In this phenomenon, satellite charging occurs in geostationary orbit due to the inflow of high-temperature plasma transferred from the tail (in what is known as plasma injection).

2.2 Satellite charging and anomalies

An electric charge is accumulated in various parts of a satellite due to the collision of ions and electrons in space plasma, and the inflow/outflow of charged particles such as in the release of photoelectrons and secondary photoelectrons, thereby generating an electric potential in space. This phenomenon is called satellite charging. The potential — an expression of satellite charging — is divided into two types depending on how the standard of measurement is used. First, assuming zero potential in space at infinity, the potential of a satellite (typically a structural body) is called satellite potential and the charging is referred to as absolute charging. Next, in case conductors or dielectrics are not grounded to the surface or inside the satellite, the difference in potential is formed between these components and the satellite's structural body. This difference in potential is known as the differential charging voltage. The charging is also divided into two types depending on the location of charging: surface charging and internal charging.

In absolute charging on the satellite's surface, the following types of electric current flow: ion current due to the inflow of ions from the surrounding plasma, electron current due to the inflow of electrons, photoelectron current due to the ejection of photoelectrons from a surface receiving sunlight, secondary electron current due to secondary electron ejection caused by the collision of plasma particles with the satellite, and backscattering electron current. The satellite potential is determined by the total sum of these currents flowing through the satellite's surface and

satellite capacitance with respect to cosmic space. The currents flowing in the satellite are governed by electron current, since electrons are much lighter in mass than ions. In addition, the secondary and backscattering electron currents are negligible, being much smaller than the electron current. Since the photoelectron current is generally larger than the electron current and only has low energy of several eV, a satellite has the potential of only several V (volts) higher than that of the surrounding plasma. If no photoelectron ejection occurs due to a satellite in the shadow (eclipse) of the earth or increased electron current due to more high-temperature electrons generated by magnetospheric substorms in the surrounding space, the total sum of currents flowing into the satellite becomes a negative value, sometimes causing a satellite potential of minus 10,000 V^{[3][4]}. Since the satellite capacitance relative to cosmic space is small, however, the electric charge accumulated due to absolute charging is fractional, and the risk to the satellite is considered low. Conversely, if a conductor or dielectric body not grounded to the satellite's structural body exists on the satellite's surface, it functions as a capacitor with the satellite capacitance and a differential charging voltage develops with respect to the satellite's structural body during the process of absolute charging. This capacitance is larger than that of the satellite's structural body relative to cosmic space, depending on location and the large amount of electric charge accumulated. A sudden electric discharge of this accumulated electric charge to the satellite's structural body may cause electromagnetic noise or such physical damage as a broken insulator and the dissolution or vaporization of materials, thereby resulting in satellite anomalies. The electrons in energy of several to more than a dozen keV that are not reflected from the satellite or which do not pass through the satellite's surface contribute to the development of the satellite's surface potential.

The internal charging is caused by the electric charge accumulated in an ungrounded conductor or dielectric body such as an elec-

tronic substrate or cable coating. The charging process of a satellite is complex, as plasma particles reach deep inside the satellite from various directions through the satellite's surface; the electrons in energy of about 100 keV are considered a contributing factor. The internal charging may also cause satellite anomalies through electromagnetic noise or damage to a circuit or substrate due to a broken insulator.

2.3 Space weather

Space weather is used for predicting space environmental fluctuations and various phenomena occurring on the ground that originate in the space environment. In particular, magnetospheric substorms and magnetic storms can actually help prevent satellite anomalies originating in the space plasma environment. That is, predicting a deteriorated space plasma environment can prevent the occurrence of serious satellite anomalies by limiting mission-critical operations such as altering the attitude of a satellite during such deterioration and pinpointing possible causes of anomalies, in order to take measures in case anomalies occur.

3 Magnetospheric simulation and prediction of the plasma environment

3.1 Real-time magnetospheric simulation

NICT is conducting magnetospheric simulation in real time by using the calculative approach of three-dimensional magnetohydrodynamics (MHD) [5][6]. Figure 1 illustrates an outline of the system. The ACE (Advanced Composition Explorer) satellite is located at Lagrange Point No. 1 (of sun-earth gravitational equilibrium) at a distance of about 1,500,000 km from the earth toward the sun, transmitting observational data on solar wind to the earth in real time. With successive input parameters of solar wind density, temperature, velocity and magnetic field being transmitted by the ACE satellite, magnetospheric simulation is conducted in real time by using supercomputers. The solar wind has an average velocity of about 400 km/s; the wind passing the ACE satellite reaches the geomagnetosphere in about an hour. Thus, the calculation results are used to predict magnetospheric conditions an hour in advance. This information is also disclosed on the website in real time.

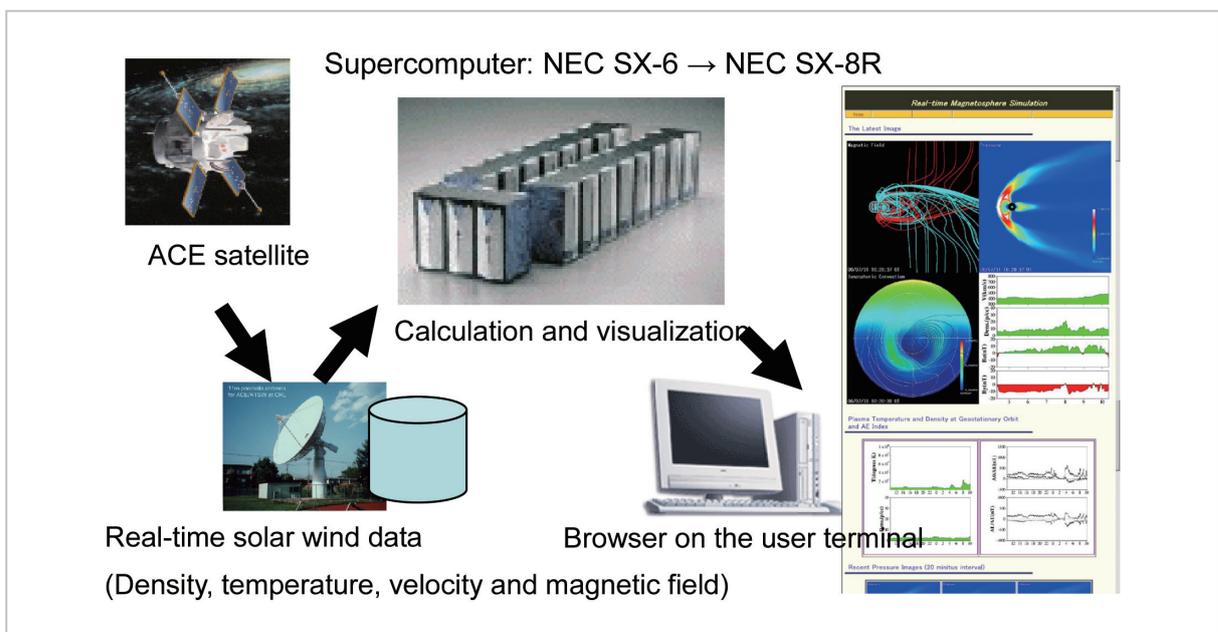


Fig. 1 Outline of the real-time magnetospheric simulation system at NICT

3.2 Approach and calculation results

The MHD calculative approach is used for magnetospheric simulation. This approach approximately resolves an issue by assuming plasma comprised of ions and electrons as one fluid, and can practically calculate the fluid movement of ions — accounting for a large portion of the plasma mass — in high speed. Figure 2 shows the calculation results obtained at 09:28 UT on February 15, 2006. A loop structure of magnetic lines is formed in the magnetotail, where a high-pressure domain of plasma is observed. This domain (called plasmoid) is ejected toward the magnetotail. A reverse flow is generated toward the earth concurrently with occurrence of the plasmoid, thereby increasing plasma pressure in the inner magnetospheric domain. This corresponds to plasma injection, indicating that the simulation results qualitatively reproduce the occurrence of magnetospheric substorms. The figures are updated about every minute and archived daily in the form of video images.

As such, MHD calculation enables real-time simulation of the magnetosphere. However, it cannot handle the particle aspects of

plasma due to the fluid approximation. Specifically, MHD calculation cannot properly handle particle heating and acceleration or drift motion in the domain of the inner magnetosphere's intense magnetic field caused by the particle effect. There is also the issue regarding the practical handling of only ion fluid motion in MHD calculation, even though electrons with energy of several to several tens of keV are known to play a key role in the geostationary orbit plasma environment, thereby contributing to satellite surface charging [7].

3.3 Comparative study with observation

For a comparison of the calculation results with observational data, we used the 5-minute averages of ion and electron densities (0.13 to 45 keV/e and 0.03 to 45 keV/q, respectively) and respective temperatures (averaged values of parallel and vertical components of the magnetic field) disclosed as key parameters of the Magnetospheric Plasma Analyzer (MPA) installed on the geostationary satellite of the Los Alamos National Laboratory (LANL). Figure 3 illustrates the calculation results and

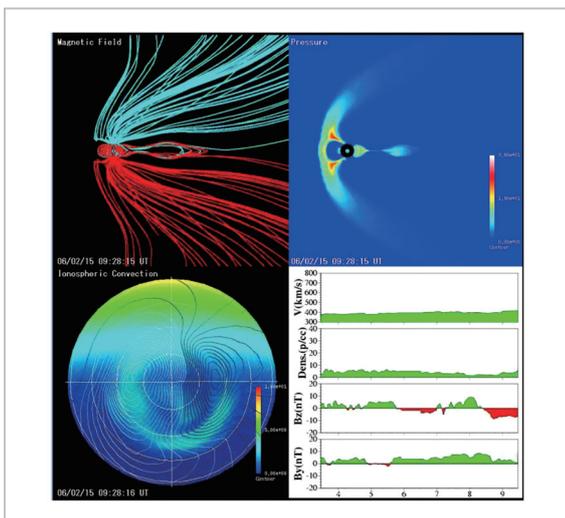


Fig.2 Data provided by real-time magnetospheric simulation at 09:28 UT on February 15, 2006: Magnetic lines (upper left), plasma pressure distribution within the meridian plane (upper right), equipotential lines and electric conductance distribution of the polar ionosphere (lower left), and solar wind used for calculation 6 hours immediately prior to simulation time (lower right)

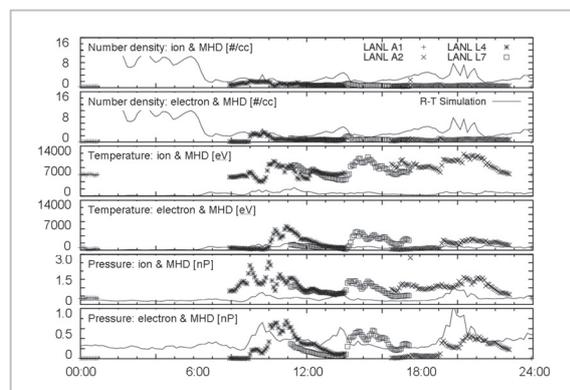


Fig.3 From top to bottom, shows 5-minute averages of density, temperature, and pressure of ions and electrons on the night side (MLT: 21:00 to 3:00) for each of four LANL geostationary satellites (A2, A1, L4 and L7) observed on February 15, 2006, being superposed with the density, temperature and pressure provided at the midnight position of geostationary orbit in the magnetospheric simulation. The increase in pressure shown in the calculation results precedes that in the observation by about an hour, or equivalent to the time it takes for solar wind to arrive.

observational data for February 15, 2006. Note that the calculation results shown are those at the midnight position of geostationary orbit and the observational data on the night side during the period from 21:00 to 03:00 in magnetic local time (MLT), as plasma injection due to magnetospheric substorms is focused. Three counts of increases in pressure were found on this day in each calculation result and the observational data. When considering the calculation results indicating the magnetosphere about an hour later, the results are understood to predict the occurrence of plasma injection an hour in advance. However, for ions, it is understood from the figure that the observational data on density, temperature and pressure are not quantitatively consistent with the calculation results. Conversely, when focusing on pressure fluctuations in the electrons, the calculation results and observational data are quantitatively and relatively consistent with one another [8]. As the reason for the quantitative consistency of electrons in terms of pressure fluctuations provided by the electromagnetic fluid calculation, the electrons are presumably influenced by increased pressure due to the fluid adiabatic process from the magnetotail in the plasma injection process. However, no quantitative consistency was found in electron density and temperature; the density resulting from calculation is much larger than that observed in most cases. Since the electron temperature contributes significantly to satellite charging, we estimated the electron density based on observational statistics, and then compared the temperature estimated from the estimated density and calculated pressure with the electron temperature provided by observation. The timing of the increase in temperature and the increased temperature noted in observation were consequently found to be a better estimation than that of electron pressure [9]. Figure 4 illustrates a comparison of electron temperatures estimated by this method and provided by observation for the period from January to April 2006. Almost all points are distributed below the line drawn in the figure, where the

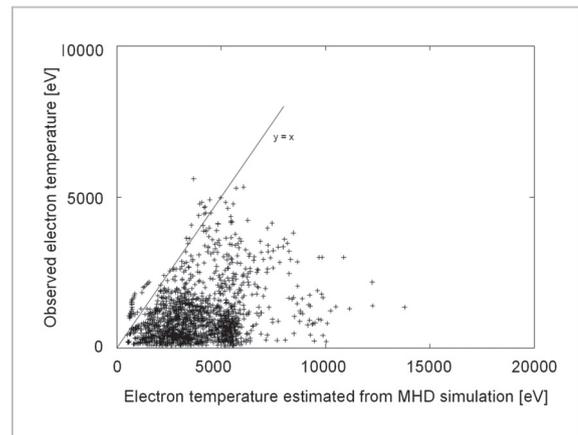


Fig.4 Dispersion diagram for electron temperature estimated by assuming electron density of 0.5 electrons/cc based on pressure resulting from magnetospheric simulation from January to April 2006, and for that observed an hour later.

estimated electron temperature equals that observed. That is, this line indicates the upper limit of observed electron temperature. However, the electron temperature is understood as being overestimated in most cases. The reasoning behind this understanding is as follows: magnetospheric disturbance tends to be retained longer in the calculation than in observation; there is a period where a higher baseline is considered to exist due to the numerical noise resulting from calculation even during a quiet period; and an increase in electron temperature or pressure is practically considered a local phenomenon, and thus the maximum electron temperature in geostationary orbit is not necessarily observed by a satellite. Further analysis and verification are still required.

3.4 Prediction of satellite charging

The worst value of satellite potential is predictable by using the estimated electron temperature. For calculating the satellite potential, we used a correspondence table of the potential and differential voltage for the plasma environment, and data observed by geostationary orbit satellite *KIKU* No. 8 (ETS-VIII) as provided by past studies [10]. Note that determining the satellite potential requires electron density and ion temperature/density in addition to the elec-

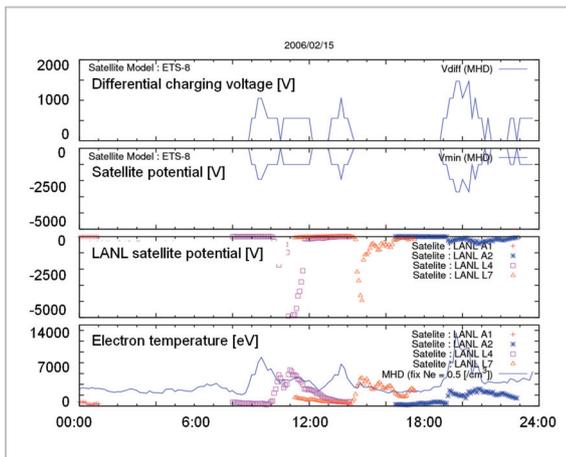


Fig.5 From top to bottom, estimated differential charging voltage of KIKU No. 8 (ETS-VIII) on February 15, 2006, estimated satellite potential, measured satellite potential of four LANL geostationary orbit satellites (A2, A1, L4 and L7) on the night side (21:00 to 3:00 at MLT), and the estimated and observed electron temperatures.

tron temperature. In this study, we also estimated ion temperature and density by using statistical values from observation similarly to electron density. Figure 5 shows the estimated worst value of the differential charging voltage and satellite potential of geostationary orbit satellite ETS-VIII [11]. This figure reveals that generation of the satellite potential can be predicted about an hour in advance. However, the value of the potential differs from the satellite potential observed by the LANL satellites. The reasoning for the difference is considered the difference in satellite interactions with the space plasma environment or insufficient accuracy of the model used for the estimation.

4 Summary

Satellites in geostationary orbit constitute an essential part of the infrastructure for mod-

ern society, and the prediction of plasma environment fluctuations causing satellite anomalies is an important issue for studies on space weather. This report described a method of estimating plasma environmental fluctuations regarding geostationary orbit, particularly the upper-limit electron temperature considered most influential to satellite charging, by using the results obtained from real-time magnetospheric simulation conducted by NICT. The worst value of geostationary orbit satellite potential can be predicted by combining this outcome with the relation between the plasma environment and satellite potential resulting from a separate calculation. Combining these findings with real-time output from real-time magnetospheric simulation enables the construction of a satellite charging alarm system and provides information about satellite operation organizations. In the current real-time magnetospheric simulation, the increased value in pressure resulting from the simulation and observational electron pressure are relatively consistent for many independent magnetospheric substorms; conversely, in periods when magnetospheric disturbances are retained or the pressure baseline is considered increased due to the numerical noise resulting from calculation, the simulated pressure is larger than the observational electron pressure, resulting in electron temperature being overestimated. The estimation is thus currently limited to determining the upper-limit electron temperature. However, we expect that this issue to be resolved by using next — generation, real-time magnetospheric simulation with improved calculation accuracy in predicting the geostationary orbit plasma environment and thus enabling a direct estimation of electron temperature and satellite potential, but not the upper limit or worst value.

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NAKAMURA Masao, Ph.D.

*Associate Professor, Department of
Aerospace Engineering, Osaka
Prefecture University*

*Space Plasma Physics, Space
Environment Engineering*