1 Space Weather and its Hazards on the High-Tech System

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In the era of 21st century space applications, the social and economic significance of satellite communications, broadcasting, and positioning will undoubtedly continue to grow. Plans are already being drawn up for manned space activities aboard the space station currently under construction. Space radiation can have undesirable effects on such activity, triggering malfunctions of semiconductor devices and degrading solar battery panels, and cause incidents that can render entire satellites nonfunctional. Other undesirable effects of space weather phenomena include disruption of aeronautic and ship radio communications and overseas broadcasting by abnormal ionization in the ionosphere (the Dellinger phenomenon), damage to power transmission lines and power feed equipment of submarine cables by geomagnetically-induced currents during geomagnetic storms, errors in satellite positioning and degraded satellite imaging due to ionospheric storms, and erratic orbital and attitude control of satellites due to heating of the upper atmosphere. In an incident occurring July 2000, attitude control for a Japanese scientific satellite was lost, resulting in the satellite falling to Earth. In February 1994 and September and November 2001, the Japanese broadcast satellite was temporarily lost from service for periods of time. Other countries have experienced similar incidents. Both Canada and the United States have experienced serious breakdowns involving several communication satellites within the past 5 years. Space weather information and forecasting is an essential service in today's increasingly satellite-reliant high-tech world, in which even satellite applications such as acquisition of precise terrain information and guided aircraft landings using GPS are currently being considered. The Communications Research Laboratory (CRL) has engaged in research on forecasts and warnings for the radio propagation via the ionosphere since 1957. From 1988, CRL expanded its research activity to encompass space weather forecasting as a whole. The CRL makes optical and radio observations of the solar surface, polar radar, and geomagnetic observations, ionosphere observations, and receives data from solar wind observation satellites. We are also developing and installing data collection and distribution systems and developing solar observation satellites. Based on the resulting data, studies have been launched to analyze the current state of space weather conditions and to anticipate future changes. This special report is released in two parts, appearing separately; the first (this) issue introduces the results of studies on space weather phenomena. The second (December) issue contains papers on observations, satellite projects, data collection and distribution systems, and forecasting methods.

Given below is a summary of various space weather phenomena observed at points lying between the Sun and the ionosphere and the hazards experienced by satellites and ground-based facilities associated with them.

The Sun is the energy source that determines the environment of our solar system. High-energy particles that cause satellite malfunctions and radiation exposure in humans, X-rays that cause the Dellinger phenomenon, and plasma cloud that cause geomagnetic and ionospheric storms are all ejected from the Sun during solar flares and coronal mass ejections (CME). X-rays reach Earth at the speed of light, exposing the Earth continuously from one to several hours. High energy particles may arrive as early as 30 minutes after a solar flare event, exposing the Earth for several days. Taking approximately 2 days to arrive at Earth, the plasma clouds cause polar storms and large-scale geomagnetic storms through interactions with the Earth's magnetosphere. High-speed plasma flows streaming from the coronal hole recurrently arrives at Earth, even during periods of solar quiescence, causing geomagnetic disturbances with cycles coinciding with the solar rotational period of 27 days. High-energy solar particles penetrate to the geostationary orbit, directly affecting satellite performance and generating various hazards. One example is the temporary disruption of satellite broadcasting that occurred in September 2001. Solar flares that generate solar X-rays and high-energy particles are believed to be caused by magnetic reconnection processes at sunspots. Observations have also indicated that solar wind shocks contribute to the generation of high-energy particles. Four papers in Chapter 2, "The Sun and Solar Wind," provide a detailed presentation of studies of the solar surface and solar wind phenomena.

When solar plasma reaches the magnetosphere (enters the range of the Earth's magnetic field, or approximately 100,000 km from the Earth), it triggers large-scale motions of the plasma confined in the magnetosphere and ionosphere. In turn, these motions generate small storms (substorms) and large geomagnetic storms inside the magnetosphere, creating radiation belts that lead to satellite malfunctions. The probability of satellite instrument malfunctions increases when concentrations of electrons with energy of 1 MeV exceed 10,000/cc in geostationary orbit. Substorms generally last from one to a couple of hours and occur at rates of several substorms per day; geomagnetic storms occur about once a month.

Substorms or geomagnetic storms generate auroras in the polar regions and flows of strong electric currents in the ionosphere. Along with auroral brightening, hot plasma is injected into the geostationary orbit from the tail side of the magnetosphere, resulting in charge accumulation in satellites. This also causes significant fluctuations in the magnetic fields at the geostationary orbit, which affects magnetic-torque-based attitude controls. Six papers in Chapter 3, "The Magnetosphere," present detailed studies of magnetospheric plasma convection, geomagnetic storm development, and production of radiation belt particles.

During major geomagnetic storms, auroras are visible even in Hokkaido. These storms heat the upper atmosphere, with major consequences for satellite orbits and attitudes. Such heating destabilized the attitude of the scientific satellite in July 2000. Extremely large storms also cause distortions in meteorological satellite imaging and scintillations in the radio intensities of ground communications, including aeronautical radios and communication and broadcasting satellites. Auroras are accompanied by electric currents as large as 1 million A, which flow in the ionosphere, inducing currents in power transmission lines and pipelines. On March 13, 1989, such induced currents in power grids caused a major power failure in Canada. A paper in Chapter 4, "The Ionosphere and the Thermosphere," discusses a detailed study of ionospheric storms.

The space weather forecasting requires various types of models. The CRL has developed a method for predicting the development of ring currents during geomagnetic storms, using a technique based on neural networks, and is currently using this system to provide real-time forecasts by inputting solar wind data. (See the December issue.) Solving 3-D MHD equations has made it possible to perform quantitative forecasting. It is now possible to forecast the occurrence of a magnetospheric substorm and its development. On the horizon is geomagnetic storm forecasting based on MHD codes, made possible by the ever-increasing computing power at our disposal. To improve forecasting precision, CRL plans to develop methods to solve equations of motion for the charged particles that make up the magnetosphere. Two papers in Chapter 3, "The Magnetosphere," provide detailed discussions of simulations.

The dramatic developments in observations of the Sun, solar winds, magnetosphere, and ionosphere, and computer simulations have led to significant progress in both the quality and quantity of space weather studies. These include advances in the physics of complex 3-D systems, which have made possible new studies of the magnetosphere and ionosphere, the environment in which satellites operate. The purpose of this special report is to present both an overview of past space weather studies and a prospectus for new space weather studies.

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