4-1-3 Space Weather Forecast Using Real-time Data

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In recent years, advances in telecommunications technology have made it possible to collect space-based and ground-based observation data needed for space weather forecasts in near real-time. Real-time data also make it possible to recognize the space environment conditions through continuous monitoring and the nowcast of space weather for issuing necessary warnings about space storms. Moreover, many other applications are conceivable, such as numerical predictions using real-time data as inputs in a prediction model. This paper describes the roles of real-time space weather monitoring.

Keywords
Real-time monitoring, Space weather, International Space Environment Service, International Geophysical Year

1 Introduction

An international joint research project called the International Geophysical Year (IGY) was conducted from 1957 to 1958. For the IGY, worldwide observation networks and data centers called the World Data Center (WDC) were developed to study the ionosphere, geomagnetic field, the sun, cosmic rays, and other topics of interest.

During this IGY period, a 24-hour forecast of geomagnetic storms called Space World Interval (SWI) was exchanged among participating institutions for joint international observation of the sun and the earth's environment. This SWI is one origin of space weather information service provided by the International Space Environment Service (ISES). In Japan, the Radio Research Laboratories (today's National Institute of Information and Communications Technology) conducted the SWI. At the time of the IGY, there was no means of communications capable of sending large quantities of data immediately; thus, observation information was encoded and sent to different sites by telex. Each site then converted the information into Morse code and broadcasted it by shortwave. Figure 1 shows an example of encoded observation data. These activities were later inherited to form the International URSIgram and World Days Service (IUWDS). Figure 2 shows the information exchange in international collaboration in the IUWDS.

Among the events held during the days of the IGY were humankind's first artificial satellite launched by the Soviet Union (today's Russian Republic), the launch of *Sputnik 1*, and the discovery of the radiation belt by *Explorer 1*, the U.S. artificial satellite. More than half a century has passed since that time,

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Fig.1 *Example of encoded observation data*

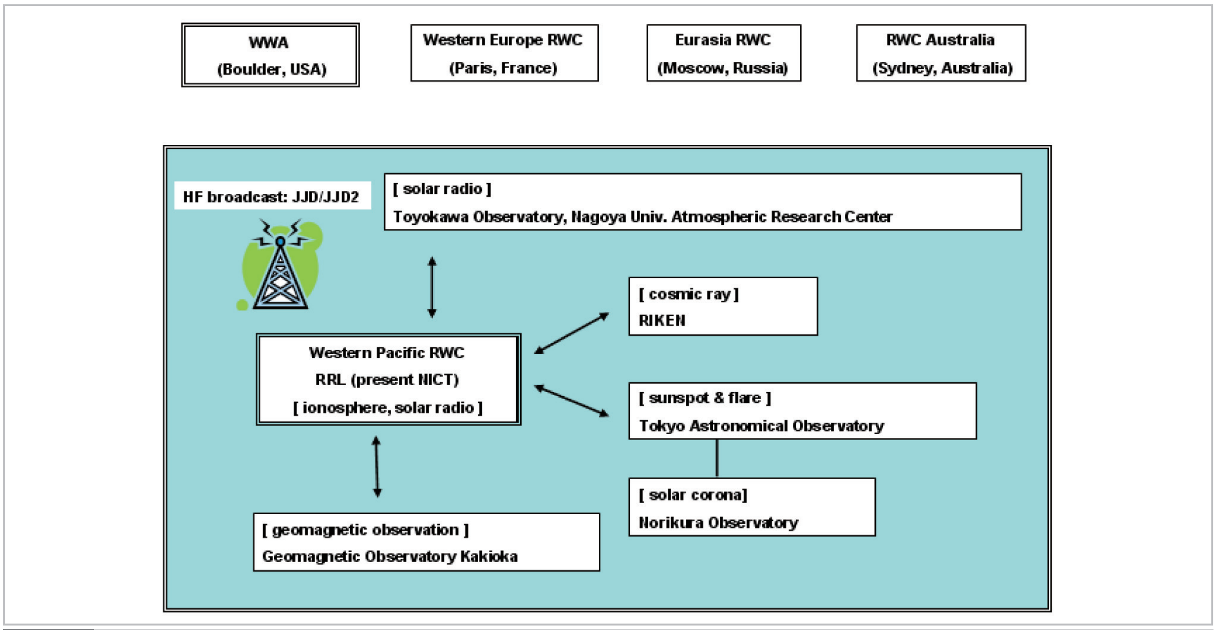

Fig.2 *Information exchange by international collaboration in the IUWDS*

and numerous artificial satellites are now being used for communications, broadcasting, positioning, meteorological observation, and other purposes. Through satellite disruptions experienced due to the effects of the space environment, people recognize the need to predict the space environment (known as “space weather”) that affects manmade technological systems in space and on the ground. The IUWDS was renamed the International Space Environment Service (ISES) in 1996 as an international organization for such space weather forecast. And now, people around the world are conducting research on space weather[1]-[3].

The rapid spread of the fast Internet in recent years has made it possible to obtain large quantities of observation data from ground-based observatories and satellites on an almost real-time basis. This in turn has made it possible to proceed with joint observations while monitoring observation data obtained from those ground-based observatories and satellites, and has expanded the range of possible joint observations, such as flexibly modifying the object of observation according to the object’s activity. In space weather, it has become possible to continuously monitor the space environment by using real-time data, thereby recognizing that status. Another thing made possible is automatically detecting the arrival of solar energetic particles, interplanetary shocks, and other hazardous phenomena, for which warnings are sent to users. Real-time data from satellites and ground-based observation networks are monitored at the Japanese Space Weather Forecast Center of the National Institute of Information and Communications Technology (NICT) as indicated in Fig. 3 and, in case a space storm occurs, a warning is sent to the users. Such real-time data can be used not only to recognize the space environment conditions but also as inputs for a prediction model. The use of a prediction model will hopefully increase the precision of prediction. NICT has been attempting to predict the geomagnetic Dst index with a neural network by using real-time solar wind data[4]. The simulation model of the earth’s magnetosphere using magnetohydrodynamic code is calculated in a near real-time manner with real-time solar wind data. NICT has been developing real-time simulation models of the ionosphere and of the sun and solar wind. The simulation model of the ionosphere is calculated by using the results of

Fig.3 NICT's Japanese Space Weather Forecast Center that monitors real-time data from satellites and ground-based observation networks

the magnetosphere simulation model. The simulation model of the sun and solar wind uses solar magnetic field data as input.

One effective way to collect real-time data from observation points without a well-established communication infrastructure is by using artificial satellites. One ongoing pioneering project for collecting real-time data using artificial satellites is an international project called the INTERMAGNET (International Real-time Magnetic Observatory) that was launched at the end of the 1980s[6]. To collect geomagnetic data from observation points, the INTERMAGNET uses the communication channels of meteorological satellites (*GOES, Himawari*, and *Meteosat*). NICT became a member of the INTERMAGNET and has collected geomagnetic data on a real-time basis from the Kakioka Magnetic Observatory, the Memambetsu Magnetic Observatory, and other observatories using the meteorological satellite *Himawari*.

This paper describes the usefulness of real-time data on space weather, including examples of NICT[7].

2 Space storm warnings based on real-time data

Real-time data enables contentious monitoring of the space environment in order to recognize the conditions thereof. This makes it

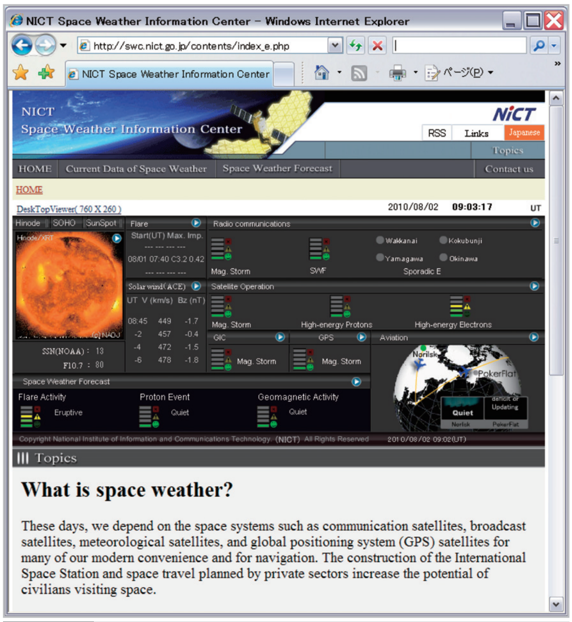

Fig.4 Webpage that provides space weather information

possible to issue early warnings to users regarding the arrival of solar energetic particles, occurrence of geomagnetic storms, enhancement of high-energy electron flux on a geosynchronous orbit, and other phenomena hazardous to technological systems. Another possibility is detecting the occurrence of a hazardous space environment automatically and then issuing warnings about space storms. For example, Shinohara et al[8]. developed an automatic detection system for Storm Sudden Commencement (SSC) based on real-time data from NICT's ground-based geomagnetic observation network. This system uses real-time data from the geomagnetic observation network to automatically detect impulsive changes in the geomagnetic field associated with the arrival of interplanetary shocks using the maximum values of amplitude, rise time and temporal change, and then reports the results of detection by email. Figure 4 is a webpage of space weather information showing the onset of geomagnetic storms, occurrence of Dellinger phenomenon, arrival of solar energetic particles, enhancement of high-energy electron flux, and occurrence of a sporadic E layer by automatic detection[9]. Near real-time data from the U.S. meteorological satellite *GOES*, solar X-rays, solar high-energy particles, and high-energy electrons are used for the automatic detection of events.

3 Real-time data as inputs for the space weather forecast model

Real-time data can be used as inputs for a prediction model. The use of a prediction model will hopefully increase the precision of prediction. The NASA-launched *ACE* (Advanced Composition Explorer) spacecraft has been observing solar wind at point L1 where the sun and earth are balanced in gravity upstream from the earth by approximately 1.5 million km, and continuously sending solar wind data on a real-time basis since 1997. NICT has been sharing the reception of real-time data from the *ACE* spacecraft in cooperation with the National Oceanic and Atmospheric Administration/Space Weather Prediction Center (NOAA/SWPC) [10]. Real-time solar wind data from the *ACE* spacecraft enables the arrival of solar wind disturbances to be detected from approximately 30 minutes to one hour before reaching the earth. One attempt to use real-time solar wind data is the reception of data from the International Sun Earth Explorer 3 (ISEE-3) spacecraft conducted from March 1980 to mid-1982 by NOAA/SEC (today's NOAA/SWPC) with the cooperation of NASA for early warnings about geomagnetic storms. At that time, data was used mainly to monitor solar wind conditions [11].

Several prediction systems have been developed based on a neural network model by using real-time solar wind data. Watanabe

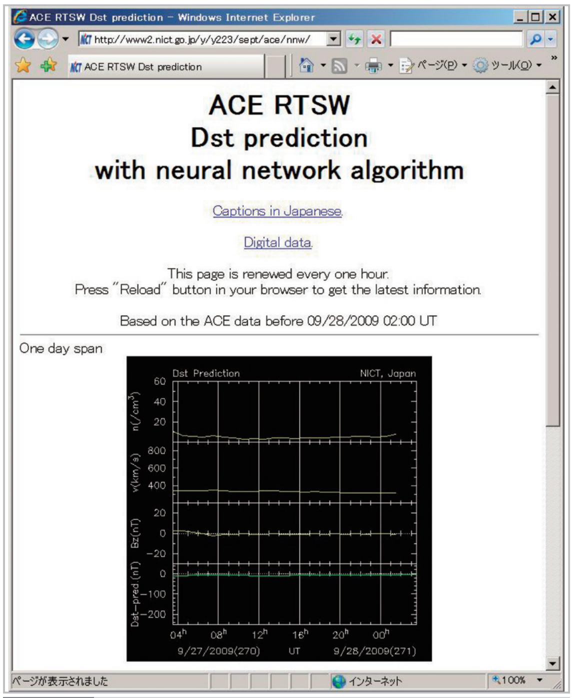

Fig.5 Prediction of the Dst index based on a neural network using real-time data as inputs

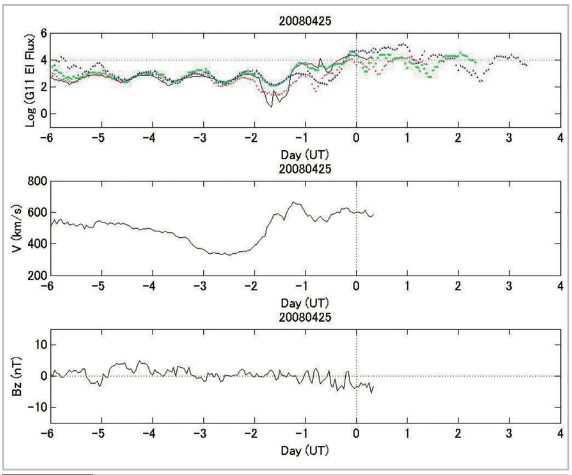

Fig.6 Prediction of high-energy electron flux on a geosynchronous orbit based on a neural network using real-time data as inputs

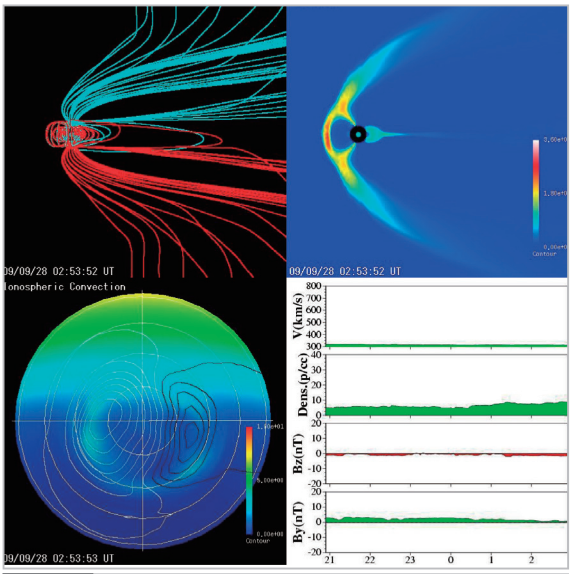

Fig.7 Results of real-time simulation of the earth's magnetosphere based on magnetohydrodynamic code using real-time solar wind data as inputs

et al[3]. developed a prediction model for the geomagnetic Dst index, an indicator of geomagnetic storms, by using the Elman neural network. Watanabe et al[3]. used real-time solar wind data (e.g., velocity, density, magnetic field intensity, x, y, and z components of the magnetic field) as inputs. Figure 5 shows an example of Dst index predictions based on this model. Watari et al[12]. developed a prediction model of high-energy electron flux variations on a geosynchronous orbit based on a neural network. An enhancement of high-energy electron flux on a geosynchronous orbit causes artificial satellite failure due to deep dielectric charging. Therefore, the prediction of such enhancements is necessary. High-energy electron flux on a geosynchronous orbit can be predicted 24 hours in advance by using present high-energy electron flux observed by the *GOES* satellite and real-time solar wind data from the *ACE* spacecraft. Figure 6 shows an example of predicting high-energy electron flux on a geosynchronous orbit based on this model.

Real-time solar wind data can also be used as inputs for a numerical model. Figure 7 shows the results of real-time simulation of the earth's magnetosphere, as developed by NICT based on magnetohydrodynamic code using real-time solar wind data as inputs[4]. Results of this simulation are open to the public on a webpage. The geomagnetic index called the auroral electrojet (AE) index—an indicator of aurora activity—is calculated by using the results of this simulation[13].

4 Roles of real-time data in space weather research

Real-time data has made it possible to continuously monitor data from space-based and ground-based observations. This increases the flexibility of joint observations. For example, this has made it easier to flexibly change observation timing and the object of observation according to the status of the object's activity, by such means as determining the timing for launching an observation rocket. The continuous monitoring of real-time data opens up the possibility of discovering new phenomena from hitherto unrecognized real-time data streams. Moreover, the real-time acquisition of data makes it possible to verify ideas by promptly referring to relevant data whenever a new phenomenon is discovered.

5 Real-time space weather data as materials for education and public outreach

Real-time space weather data are excellent materials for education and public outreach. Images of auroras and the sun provided on a real-time basis allow the general public to become more familiar with present space weather conditions. For example, the *SOHO* (Solar and Heliospheric Observatory) spacecraft launched by ESA and NASA allows near real-time images of the sun taken by white light, extreme ultraviolet, and coronagraphs to be made available to the public on the webpage shown in Fig. 8[14]. Thus, the general public can access the webpage and enjoy the real-time solar images.

Space weather sometimes affects our daily lives and could be the entry point for attracting public interest in space sciences. For example, when a strong geomagnetic storm occurred in March 1989, a geomagnetically-

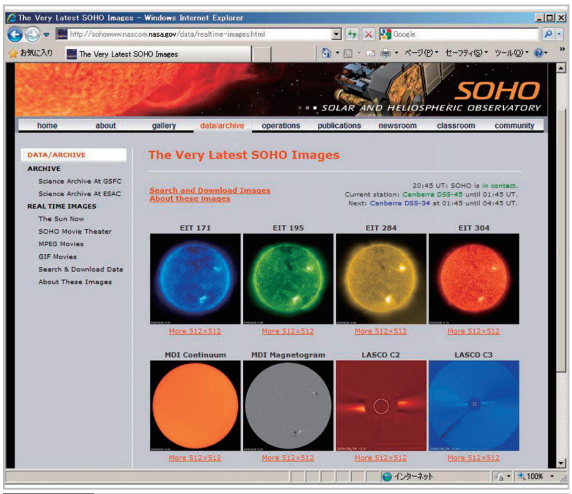

Fig.8 Webpage of near real-time solar images from the SOHO spacecraft

induced current caused a major power blackout in Canada's province of Quebec, affecting about six million people[15]. Moreover, space storms disrupt communication satellites and broadcasting satellites, even resulting in communication and broadcasting services being occasionally interrupted[16].

6 Technology needed for real-time monitoring

The global deployment of an observation network to collect real-time data requires careful consideration of how that data is to be collected, securing a power supply, providing maintenance in case of equipment breakdown, and other matters. At unattended observation points, the recovery from equipment trouble is particularly difficult. One must therefore consider building a highly reliable system, installing observation points at locations offering easier access in case of trouble, and other matters. Regarding the power supply, there are cases where no power supply is available or, even if available, a blackout may occur or voltage may become unstable. It is also necessary to take measures against blackouts by using an uninterruptible power supply, solar batteries, wind generators or similar equipment, or to develop equipment operating at low power consumption. When installing an observation point at a location without a well-established communication infrastructure as a means of collecting data, one conceivable idea for collecting data on a real-time basis is to use artificial satellites. For example, the Iridium satellite system engages in mutual communications among 66 satellites that orbit the earth at an altitude of about 780 km, thereby achieving a global communication network by using small terminals. The main problem posed by this system is its still high communication charges, but the use of the Iridium system enables the collection of data on an almost real-time basis from global ground-based observation networks. The National Institute of Polar Research in Japan has developed unattended geomagnetic observation equipment using the Iridium system for data transmission, and has thus built a wide-ranging geomagnetic observation network in Antarctica[17]. As a ground-based communication network, the network of mobile telephony is rapidly spreading, making real-time data collection based on mobile telephony conceivable. Moreover, given the higher performance and lower costs of wireless networking equipment, the use of a wireless network between an observation point and the nearest access point of an Internet network makes it possible to build a data collection network at relatively low cost.

7 Conclusion

To attract attention in a timely manner in response to the arrival of a space storm that may affect our technological systems, such as by disrupting artificial satellites, it is necessary to monitor the space environment at all times. Recent advances in telecommunications technology have made it possible to acquire space environment data on a real-time basis for monitoring the space environment. However, when considering whether to build a global real-time observation network, one finds that there still are regions where a communication network is difficult to secure, such as the Arctic and Antarctic regions. As a future challenge, hopes run high for the development of a highly reliable and relatively low-cost communication system that enables the collection of real-time data.

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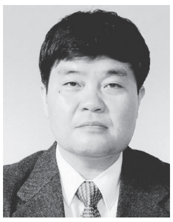

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Solar-Terrestrial Physics, Space Weather