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FEATURE

Space Weather Forecasting to Support Social Infrastructures

Interview

Protecting Society 5.0 Social Infrastructure from Solar Storms

Leading research on clarifying the mechanism and forecasting of space weather

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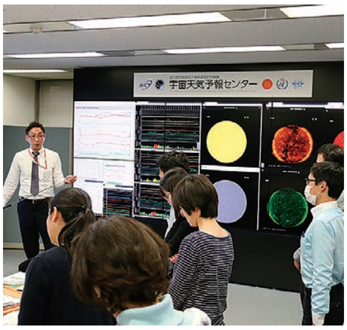

Cover photo:
An 11.3m-diameter parabolic antenna at NICT headquarter receives observation data from DSCOVR and ACE satellites, which are located at approximately 1.5 million kilometers from the Earth toward the sun and constantly monitor solar wind from the sun. Through collaboration among four countries, solar winds are monitored 24 hours a day.

Upper-left photo:
NICT Space Weather briefing room. We hold a space weather forecast meeting at 14:30 JST on weekdays and provide the information via email, a website, and SNS.

President of the National Institute of Information and Communications Technology
Dr. TOKUDA Hideyuki

Happy New Year!

Last year, ahead of the Tokyo 2020 Olympic and Paralympic Games, we identified the need to further enhance security measures against cyberattacks on Internet of Things (IoT) devices owing to the rapid adoption of these devices. In February, the Ministry of Internal Affairs and Communications and NICT launched a project called NOTICE to investigate IoT devices that may be maliciously used for cyberattacks and to alert users of such devices, in collaboration with Internet providers. In addition, the advanced technologies in the field of information and communications, such as those related to IoT, Big Data, artificial intelligence (AI), automatic driving, and the fifth-generation mobile communication system (5G), were developed under interdisciplinary co-creation. 2019 was the year that we highly recognized the importance of "human centeredness", "sustainability", and "diversity" as basic principles of our future society in which Society 5.0 will be achieved.

NICT is the sole national research institute in the field of ICT in Japan. Our mission is to resolve social issues and create new values in relation to the advancement of information and communications technology (ICT). To fulfill this role, we are carrying out integrated research and development of world cutting-edge technologies as well as projects to promote the social development and implementation of such technologies based on the collaborative and open-innovation promotion policy.

At NICT, we are steadily promoting research and development in five clusters: sensing fundamentals, integrated ICT, data utilization and analytic platforms, cybersecurity, and frontier research. In particular, the first-ever achievements were obtained in the fields of high-capacity transmission using new types of multicore optical fibers, Beyond 5G, brain-inspired information processing and communications, post-quantum cryptography, privacy-preserving technology, and bio-ICT. In quantum cryptography communications, the first recommendation for standardization related to quantum key distribution was approved by SG13 of the International Telecommunication Union Telecommunication Standardization Sector (ITU-T). In 2019, we started providing the space weather information service to International Civil Aviation Organization (ICAO) in November and operating the space weather forecasting service around the clock in December. As part of our efforts to promote collaboration and open innovation, we have accelerated the development of human resources responsible for security by enriching the contents of practical cyber exercises that are conducted in an environment simulating the Tokyo 2020 Olympic and Paralympic Games (Cyber Colosseum) at our National Cyber Training Center. For collaboration in the field of data utilization, multilingual speech translation technology has been increasingly implemented in our society in the fields of transportation, tourism, disaster prevention, medical care, and shopping in accordance with the Global Communication Plan to eliminate language barriers. Since September 2017, we have been operating "Translation Bank" jointly with the Ministry of Internal Affairs and Communications, aiming to establish a translation ecosystem that can be used and improved by participants through the accumulation and utilization of high-quality translation data in various industry fields. In 2019, the practicality of the translation of automobile regulations was improved through cooperation with the automobile industry. NICT has also conducted joint research and demonstration projects with research institutions, companies, universities, and local governments both in Japan and overseas. Activities to provide companies with our various advanced technologies have also been carried out with public relations activities for NICT SEEDs as well as international standardization activities at the International Telecommunication Union (ITU), the Institute of Electrical and Electronics Engineers (IEEE), the Internet Engineering Task Force (IETF), and so forth.

NICT has three management policies: collaboration, an open and innovative mind, and a challenging spirit. As an attempt to organically integrate and put them into practice, NICT Open Summit was held to conduct closed discussion meetings with a small number of outside experts. Last year, "Quantum computation and AI (machine learning)" was the focus of discussion. The Ideathon/Hackathon events have continued to be held in Sendai and Hokuriku. We will solicit ideas from participants and aim to further contribute to resolving social issues in local communities using ICT. Collaboration with overseas institutions, such as those in Europe, United States, and ASEAN countries, will also be strengthened. We will continue to solicit feedback from the public regarding research and development themes that should be extensively addressed in the future and will use them for the management of NICT. Research results obtained by NICT will be available as much as possible in an improved usage environment.

This is the final year of the fourth medium- to long-term plan of NICT. To achieve its goals, we will endeavor to promote our research and development activities by concentrating resources in various fields and maximize their results. At the same time, we will prepare for the formulation of the next medium- to long-term plan to further streamline the work at NICT. To appropriately return the fruits of our research to society, we will effectively carry out our social responsibilities as a national research institute.

We will continue to hear the wide range of opinions from people throughout Japan. We will promote industry-academia-government collaborative activities in cooperation with all of those involved, continuously striving for further development of the ICT field. We appreciate your continued support and cooperation.

Lastly, I wish all of you a wonderful year in 2020.

FEATURE Space Weather Forecasting to Support Social Infrastructures

Interview

Protecting Society 5.0 Social Infrastructure from Solar Storms

Leading research on clarifying the mechanism and forecasting of space weather

Applied Electromagnetic Research Institute

TAIRA Kazumasa (left)

Director General
Applied Electromagnetic Research Institute

Joined the Communications Research Laboratory, Ministry of Posts and Telecommunications (currently NICT) in 1991. Engaged in R&D in mobile radio propagation, mobile communications systems, and electromagnetic compatibility. Held positions of Director General of Outcome Promotion Department and Director General of the Network Security Research Institute before taking his current position in April this year. Ph.D. (Engineering).

ISHII Mamoru (right)

Director of Space Environment Laboratory
Applied Electromagnetic Research Institute

After completing graduate school at in 1993, joined the Communications Research Laboratory (current NICT) in 1994. Engaged in research in upper atmosphere physics, optical measurement techniques, and radio observation. Specialist member of the Ministry of Public Management, Home Affairs, Posts and Telecommunications Commission for Data Communications. Vice Chairman of ISES, Specialist member of UN/COPUOS & WMO/IPT-SWeISS. Councilor, Society of Geomagnetism and Earth, Planetary and Space Sciences. Ph.D. (Science).

Space is an extremely violent place. High-energy particles and electromagnetic waves are emitted from the sun with explosions on its surface. The magnetosphere and atmosphere around the Earth serve as a barrier against them. However, during periods of high solar activity, the particles and waves can penetrate the magnetosphere and irradiate the surface of the Earth's atmosphere, which sometimes has a major impact on social infrastructure, such as radio utility, power networks, and global positioning system (GPS).

The research on space weather forecasting carried out at NICT aims to forecast solar storms that may cause such phenomena. How is space weather forecasting carried out? We interviewed TAIRA Kazumasa, Director General of Applied Electromagnetic Research Institute, and ISHII Mamoru, Director of Space Environment Laboratory.

Protecting society and creating new values

——I've heard that Applied Electromagnetic Research Institute is carrying out research on "observing" the real society using information and communication technology (ICT). Within that framework, what is the mission of space weather forecasting?

TAIRA The goal of the research carried out at NICT is to create new values of ICT in human society. To this end, we should obtain data by observing various phenomena and import the data into cyberspace. Applied Electromagnetic Research Institute is developing technologies to measure the environment of the real society using electromagnetic waves. We have two goals. One is to develop technologies to protect our society and the other is to create new values of science.

The space environment is significantly changed by solar activity, which causes problems in radio propagation, satellite positioning, the operation of airplanes and artificial satellites, and the power grid. These influences can have a major impact on our society. Therefore, understanding space weather is directly related to our goal of protecting society.

As for the second goal, namely, to create new values of science, there are many unclarified phenomena related to space weather. For example, the mechanism underlying the sporadic E layer, which is the layer causing extraordinal radio propagation with increased electron density at an altitude of approximately 100 km, has not been clarified yet, and it is difficult to predict its occurrence. We are trying to clarify the mechanisms underlying such phenomena and create new values of science.

ISHII One of the factors that has the most significant impact on the environment of the Earth is solar flares, namely, explosions on the surface of the sun. However, the mechanism of solar flares has not been clarified yet.

The mechanisms related to the changes in solar wind, the magnetic field, and the geomagnetic field have almost been clarified, but their prediction remains difficult.

What is space weather forecasting?

——What is space weather forecasting?

ISHII Space weather is the condition of the near-Earth space. When explosions occur on the surface of the sun, harmful high-energy particles and electromagnetic waves explode outside and in some cases toward the Earth. The Earth has two barriers against them.

One is the atmosphere of the Earth, which blocks harmful electromagnetic waves like X-rays and ultraviolet rays. The other is the magnetic field of the Earth, which shuts out charged corona gas emitted from the sun. However, when powerful solar activity called a solar storm occurs, the charged corona gas penetrates through the magnetic field under some conditions and affects the environment near the Earth. This has an adverse effect on our social infrastructure. Although large-scale solar storms occur infrequently, when they do occur, they cause severe economic loss. Therefore, countries around the world have been preparing countermeasures against changes in space weather.

In the near future, private citizens will be able to travel in space. In addition, the use of drones for home delivery using GPS with their precise positioning technology will become widespread. In such an era, space weather forecasting will be indispensable.

NICT holds a space weather forecasting meeting at 14:30 JST on weekdays, where measurement data of the sun, magnetosphere, and ionosphere are discussed to make forecasts. Then the forecast data are uploaded onto the website and distributed via email.

——Please explain the types of research and development related to space weather forecasting.

ISHII The main goal of the research related to space weather forecasting is to improve its accuracy. Because the scope of the research is wide, specialists in solar physics, the magnetosphere, the ionosphere, and the structure of the atmosphere carry out their research in their respective fields.

TAIRA The observation points on the Earth are limited to the land, and it is not possible to understand the state of the ionosphere above the sea. Therefore, we are also focusing on the simulation of space weather and have developed a simulator of the entire ionosphere.

Cooperation with outside institutions

——Please tell us about the work you are doing with other institutions.

ISHII In Japan, we collaborate with many universities, for example, Institute for Space-Earth Environmental Research (ISEE*1), Nagoya University. We have formed an alliance with institutions in other countries that carry out space weather forecasting and established an organization called International Space Environmental Service (ISES*2). Eighteen countries participate in ISES. In addition, we conduct joint research with World Meteorological Organization (WMO*3) and National Oceanic and Atmospheric Administration (NOAA*4) in the US. Moreover, countries in Asia and Oceania have become active in research on space weather forecasting, and we have launched an organization called "Asia Oceania Space Weather Alliance (AOSWA*5).

Maintaining the accuracy of new services

——Please tell us about your latest challenges.

TAIRA NICT has been accumulating measurement data from the ionosphere for about 70 years since soon after World War II. The data we collect every 15 min every day are really precious; it is not an exaggeration to say that the data are an asset of humanity. I'm thinking about how such data can be used effectively in various fields.

ISHII In the future, GPS with high precision will be used in various applications, such as automatic driving and drone operation. In addition, the number of airplanes using polar routes has been increasing recently, but polar regions are more severely affected by space weather impacts than other regions. International Civil Aviation Organization (ICAO*6) began to provide alerts of space weather for airline companies in November 2019. NICT is also providing information on space weather as the sole member of the ICAO Global Space Weather Center from Asian countries. This is a good example of how our research achievements are helpful to society.

As explained above, the development of technology to improve the accuracy of new services that are expected to become more popular in the future will be required.

Future prospects

——Please explain your future research plans.

ISHII I have been involved in research on space weather forecasting for 30 years. I would like to provide information on space weather in a form that meets the needs of users.

For example, we will provide specific positioning data for those who require such data. In addition, a consulting service to help people configure systems to increase their robustness to space weather will be required in the future. I think this trend will lead to the generation of new businesses.

TAIRA NICT is a national research institution and one of our roles is to support the activities of the private sector. NICT has accumulated measurement data and technologies and we would like to utilize them to support the activities of this sector. We feel confident that we have responded to the needs of this sector. We are planning to respond to the needs of society to protect its social infrastructure.

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*1 ISEE: Institute for Space–Earth Environmental Research
*2 ISES: International Space Environmental Service
*3 WMO: World Meteorological Organization
*4 NOAA: National Oceanic and Atmospheric Administration
*5 AOSWA: Asia Oceania Space Weather Alliance
*6 ICAO: International Civil Aviation Organization

For the Use of Radio Propagation in a New Space Era

Research of the ionosphere, the closest part of outer space

TSUGAWA Takuya

Research Manager
Space Environment Laboratory

Applied Electromagnetic Research Institute

After completing graduate school, he joined NICT in 2007 after working as a JSPS Research Fellow (Nagoya University, and Massachusetts Institute of Technology). He is engaged in research on space weather, especially the monitoring, prediction and correction of ionospheric disturbances that interfere with radio propagation. Ph.D.(Science).

The ionosphere is the closest part of outer space to the Earth. Ionospheric disturbances can cause problems in systems using radio propagation, such as Global Positioning System (GPS), communication and broadcasting satellites, and HF radio communications. In a new space era with advanced technology used for precise positioning by Global Navigation Satellite System (GNSS) and the widespread use of space weather information by private aviation communities, our research group is developing advanced technologies to nowcast the current state of the ionosphere and forecast ionospheric variations to provide related information to users of radio propagation.

Background

In the upper atmosphere at altitudes higher than the cruising altitude of airplanes and the ozone layer, the atmosphere is partly ionized into ions and electrons, that is, it is in the plasma state. This region is called the ionosphere, the closest part of outer space to the Earth. The ionospheric plasma density is the highest at the altitudes of 300–400 km, which is the orbital altitude of the International Space Station (ISS). Depending on the density and structure of the ionospheric plasma, radio waves of medium and high frequencies (MF, HF) are reflected by the ionosphere, and radio waves transmitted from spacecraft to the ground are delayed or fluctuate in the ionosphere (Figure 1).

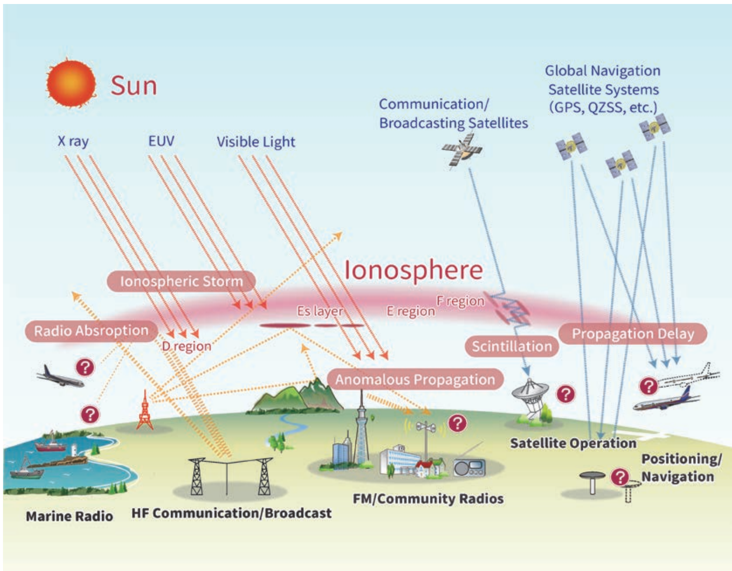

Figure 1 Ionospheric effects on radio propagation

The ionosphere varies owing to activities not only in the sun and the magnetosphere but also in the lower atmosphere. The variations in the ionosphere often cause problems in systems using radio propagation, such as HF communication/broadcasting and GNSS positioning/navigation. For example, when significant solar flares occur, the lower region of the ionosphere (altitudes of 60–90 km) is abnormally ionized by intense solar X-ray radiation, which absorbs HF radio waves, leading to the failure of HF communication. This phenomenon is known as radio blackouts or the Dellinger effect. In addition, when the disturbance due to solar wind reaches the vicinity of the Earth 2–3 days after the occurrence of solar flare, ionospheric storms occur, namely, the plasma density in the ionosphere increases or decreases more than usual. As a result, positioning errors increase in GNSS positioning/navigation systems, in which the positioning accuracy depends on ionospheric delay models. Because there are many users of such social infrastructure employing radio propagation, monitoring and prediction of the ionosphere have been carried out as one of the most important fields of space weather.

Use of radio propagation in a new space era

Space utilization has extended in our society. For example, the accuracy of positioning/navigation has improved using GNSS such as the "Japanese GPS," MICHIBIKI, and the full-scale use of space weather information by private aviation companies has begun. In such a new space era, it is necessary to develop technologies for monitoring the ionosphere with higher accuracy and less delay, for forecasting ionospheric variations and disturbances with higher reliability, and for providing data that meet user needs, such as index forecasts for communication and positioning problems. In this article, the recent research and development on these technologies are introduced.

[Monitoring of ionosphere]

NICT has been monitoring the ionospheric density profile for more than 70 years using ionosondes, which transmit HF-range radio waves with different frequencies toward the ionosphere and observe the echoes reflected in accordance with the ionospheric plasma density. Ionosonde monitoring systems are currently installed at four sites in Japan [Sarobetsu (Hokkaido), Kokubunji (Tokyo), Yamagawa (Kagoshima), and Ogimi (Okinawa)]. In 2017, the ionosonde systems were replaced by VIPIR2 with an 8ch receiving antenna array at the four sites (left, Figure 2). VIPIR2 can separate O-X modes of the ionospheric echo in the observation data (ionograms) (right, Figure 2), which enabled the derivation of more accurate ionospheric values. For example, the automatic scaling rate of the critical frequency of the ionospheric F region has been improved from 80% to 99.8% and the error (difference between the automatically scaled and manually scaled values) has decreased from 0.26 MHz to 0.12 MHz. We are planning to reduce the time required for each observation and the observation cycle from 15 min to 5 min to provide ionospheric information with less time delay.

[Forecast of ionospheric variations]

Currently, ionospheric variations are forecast on the basis of statistical calculation results using the information of the current ionospheric condition and the forecast data of geomagnetic disturbances. However, the ionosphere is also affected by the condition of the lower atmosphere. In some cases, the ionospheric variations are large even when the solar and geomagnetic activities are quiet. To improve the reliability of the forecast, it is important to integrate numerical simulations using a whole atmosphere and ionosphere coupling model and the observation data. We are developing a new data assimilation model based on GAIA (Ground-to-Topside Model of Atmosphere and Ionosphere for Aeronomy) that takes into account the interaction between the plasma in the ionosphere and the neutral atmosphere in the thermosphere and covers the region from the ground to the upper atmosphere (Figure 3).

[Data provision]

Even if the observation data are accurate and forecast data are reliable, high-level social use of ionospheric data will not advance if the data cannot be easily understood or used by users. Therefore, it is necessary to develop easy-to-use data and tools that satisfy the needs of radio propagation users. One of the user needs is indices of ionospheric storms. Unlike solar flares and geomagnetic storms, there have been no clear indices or scales for ionospheric storms, and it has been difficult to determine the level of ionospheric disturbances. We have developed a new scale for ionospheric storms, "I-scale," using long-term observation data of ionosondes and GPS total electron content. We now use the I-scale as a scale for the severity of ionospheric storms in our operation of space weather forecasts.

Future prospects

In order to meet the various needs of radio propagation users, we will steadily improve the accuracy and reduce the delay of observation, improve the reliability of forecast results, and provide data and applications to meet the needs of individual users. One such user need is the visualization of radio propagation under various ionospheric conditions. We are developing a radio propagation simulator (HF-START) that can accommodate various models and observation results as the input of ionospheric conditions (Figure 4). In the future, we are planning to enable the visualization of the propagation of radio waves transmitted by users at any frequency from any site as a web application.

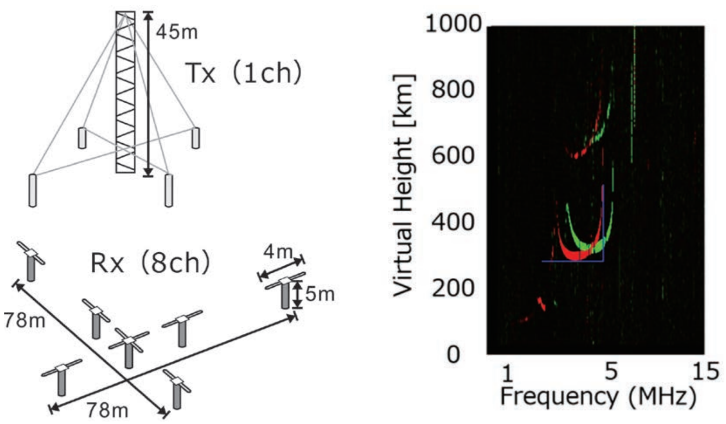

Figure 2 VIPIR2 ionosonde system (left) and observation data (ionogram, right)

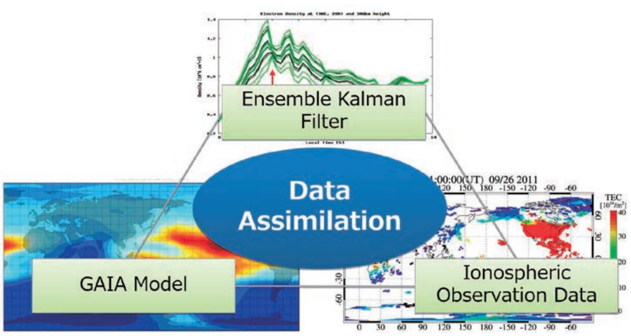

Figure 3 Development of data assimilation model based on GAIA model

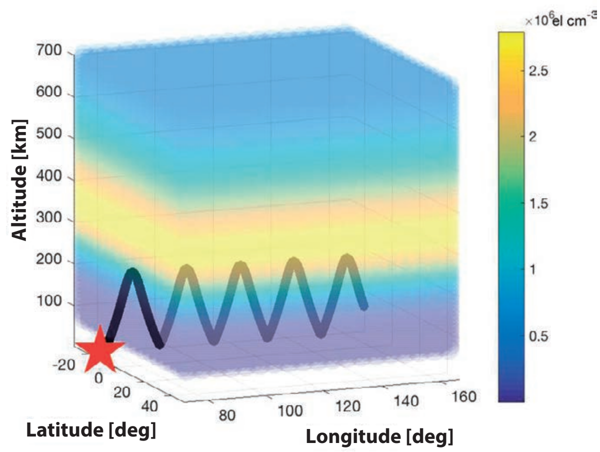

Figure 4 Development of radio propagation simulator (HF-START)

Space Weather Study for Mitigating Spacecraft Anomaly

The radiation belt forecast

SAKAGUCHI Kaori

Senior Researcher
Space Environment Laboratory

Applied Electromagnetic Research Institute

After completing her doctoral program, Dr. Sakaguchi obtained a research fellowship for young scientists from Japan Society for the Promotion of Science and then joined NICT in 2010. She is currently engaged in research on space weather, such as the forecast of the aurora and radiation belts. Ph.D. (Science).

Variations in the space environment can cause problems in spacecraft. Around the Earth, there are regions called the radiation belts (Van Allen belts), where high-energy electrons are trapped by the Earth's magnetic field. Spacecraft passing through these belts are vulnerable to high-density energetic electrons. In this article, the relationship between spacecraft and the space environment as well as our attempts to forecast the behavior of the radiation belts, which is one of the important themes of space weather research, are introduced.

Spacecraft and space environment

These days, various communication, broadcasting, and positioning services and information indispensable to our daily lives, such as location information obtained using our smartphones, have been realized owing to space infrastructure including spacecraft. According to statistics from the United Nations, the number of spacecraft operating in space near the Earth has reached more than 5,200 as of 2019. In the past, the main mission of spacecraft has been scientific observation and exploration. However, the number of spacecraft for commercial use now has surpassed that for scientific use. Recently, we have heard on the news about business developments by SpaceX and Amazon that will use several thousand small satellite constellations. If these developments are realized, our daily lives will increasingly depend on the space infrastructure. However, spacecraft are made and operated by humans, and various problems, such as system failures, communication failures, and the deterioration of solar-battery panels in outer space, are inevitable. In addition to these problems attributable to human-based factors, such as defects in the manufacturing and design process and operation errors, many problems are caused by the vulnerability of spacecraft to variations in the space environment, such as occurrences of space storms. In particular, the increases in the amount of radiation and plasma near the Earth caused by the occurrence of solar flares and magnetic storms can cause severe charging and material deterioration of spacecraft. One of the most important themes of space weather research has been the forecast of variations in the space environment in advance to reduce the risk of problems in spacecraft.

Space radiation near the Earth

Figure 1 shows the distribution of sources of radiation around the Earth. Radiation on

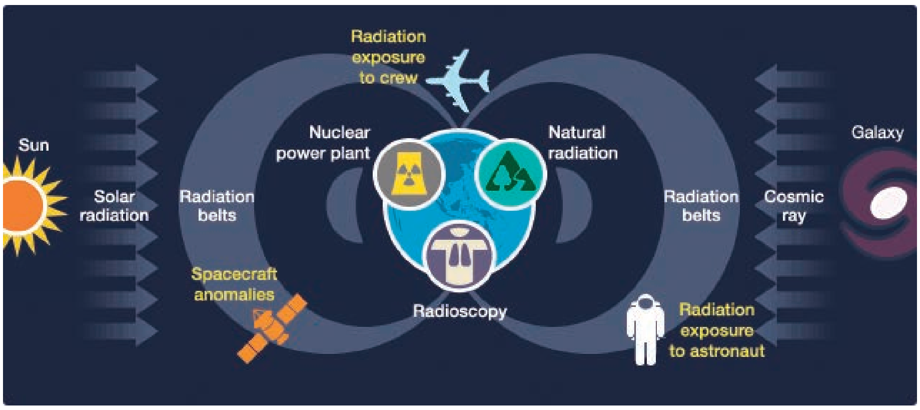

Figure 1 Sources of radiation around the Earth and their effects

the ground is known to have an adverse effect on human bodies*, whereas the radiation in space causes problems in spacecraft. The main sources of radiation in space are (1) galactic cosmic rays arriving from long distances, (2) solar radiation emitted from the sun, and (3) the radiation belts (Van Allen belts) surrounding the Earth. These are collectively called space radiation. The amount of galactic cosmic rays does not markedly vary; it fluctuates by approximately 10% with a period of 11 years. However, for solar radiation and the energetic electrons of the outer radiation belt, increases in magnitude of several orders have been frequently observed within a period of several days. In the past, severe problems in spacecraft because of marked increases in the level of space radiations have been reported after occurrences of solar flares and magnetic storms. Spacecraft in orbit generally cannot escape from space radiations. However, if we can forecast increases in the level of radiations in advance, we will be able to devise countermeasures to prevent fatal problems with artificial satellites by appropriately modifying their operation.

Radiation belt forecast

The radiation belts surround the Earth and are concentrated along dipole magnetic field of the Earth. Many spacecraft have to cross the regions of radiation belts when they orbit around the Earth. In particular, the orbits of spacecraft with high utility, i.e., the geostationary orbits (GEOs) and medium earth orbits (MEOs) used for positioning and communication services, overlap with the radiation belts. Therefore, such spacecraft are inevitable to be charged and are exposed to energetic electrons in the radiation belt for a long time. Figure 2 shows the trend of the number of days of radiation belt alerts, i.e., when the number of energetic electrons exceeded the critical level, in the past 20 years. The number of energetic electrons in the radiation belt increases in periods of the declining phase of the solar cycle of 11 years. As shown in Figure 2, the number of days of radiation belt alerts with the "high" or "extremely high" level was large between 2003 and 2008 and between 2015 and the present. In the last few years, the number of days of radiation belt alerts with the "extremely high" level has been large in the present solar cycle compared with that of the previous one. Failures of the quasi-zenith satellite system "Michibiki" have been reported, during which the number of electrons in the radiation belt was greater than that during high-level alert in this solar cycle.

Our research group is developing models to forecast the number of electrons in the radiation belt for the purpose of reducing the risk of failures of spacecraft caused by variations in the space environment. Regarding the changes of electron fluxes in the radiation belt, however, many fundamental processes have not been clarified in detail and their quantitative prediction based on numerical simulation alone has been difficult so far. Therefore, we developed an empirical model for forecasting that can learn from past data and into which recent measurement data are input [Sakaguchi et al., 2013]. Figure 3 shows a screenshot of the website of the radiation belt forecast computed by this model (http://seg-web.nict.go.jp/radi/). On this website, the expected number of electrons to which a GEO spacecraft will be exposed when it orbits the Earth over the next several days is displayed with the risk level. On the website, the real-time monitoring data of the GEO environments at the longitude of Japan collected by space environment data acquisition (SEDA) equipment installed on the geostationary meteorological satellite "Himawari-8" launched in 2015 are also published. In 2017, the "Arase" satellite for the exploration of energization and radiation in geospace was launched by JAXA in cooperation with other institutions, making possible the real-time monitoring of MEO environments. By inputting these latest data into the model, we have started providing to the public hourly forecasts of electron flux in the orbit of "Himawari" and daily forecasts of electron flux in MEO.

Future prospects

In this article, our work on radiation belt forecasting has been introduced. As explained above, besides the radiation belts, various other factors cause the failures of spacecraft, such as solar radiations, galactic cosmic rays, space plasma, and the density of the Earth's atmosphere. In addition, their effects depend on the characteristics of each spacecraft, such as the shape, material, and time spent in orbit. Therefore, the effects of the space environment differ among individual spacecraft even when the spacecraft are orbiting close to each other. Our group has been making progress in research using both a learning model and a physical model to predict the environmental variations in space. In addition, we have started a project to evaluate the risk faced by each spacecraft under variations in the space environment.

* People living on the surface of the Earth are not affected by space radiations because they rarely penetrate through the geomagnetic field and the atmosphere of the Earth. However, the crew in airplanes that fly over the polar regions and astronauts who work at the altitude of International Space Station should pay attention to the level of cosmic rays. The evaluation of this effect is also addressed as one of the important themes of space weather research.

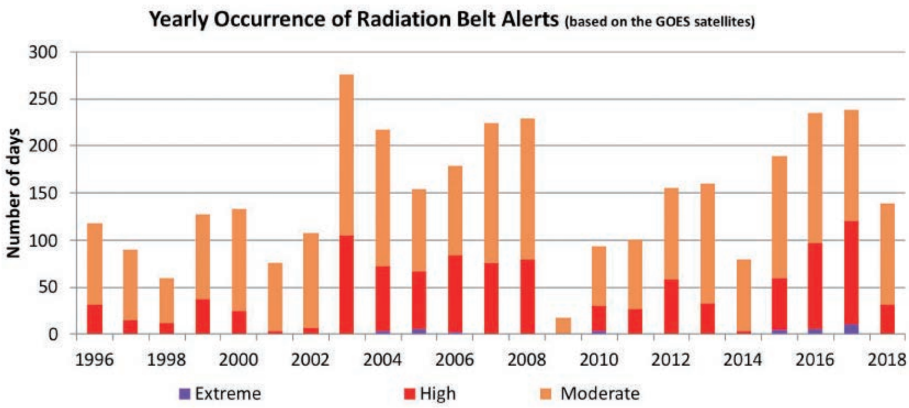

Figure 2 Yearly Occurrence of Radiation Belt Alerts for GEO spacecraft

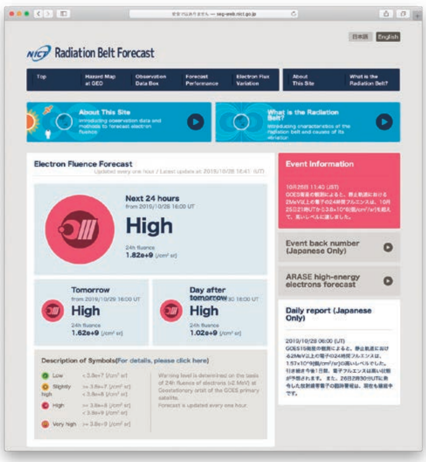

Figure 3 Website of Radiation Belt Forecast

Real-time Prediction of Solar Storm Impact

SHIOTA Daikou

Researcher
Space Environment Laboratory

Applied Electromagnetic Research Institute

He received a doctorate in 2007. He began to work in NICT as a researcher in 2017 after working in several institutes (National Astronomical Observatory of Japan, Japan Agency for Marine-Earth Science and Technology, RIKEN, and Nagoya University). He studies the physics of solar storms and develops numerical systems to predict the impact of solar storms. Ph.D.(Science).

Various technologies used in space, including wireless telecommunications, are affected by changes in space weather, which may lead to serious problems in some cases, such as the unavailability of use of services requiring these devices and systems. Among the different phenomena affecting space weather, the effects of solar storms are the most significant. Therefore, it is important to predict the impact of solar storms on the Earth's space weather in advance before the arrival of solar ejection. Our research group is developing a system that can predict the arrival of corona gas ejected from the solar corona using the results of real-time analysis of observation data of the Sun and is carrying out numerical simulation of the propagation process of the ejected corona gas with its internal magnetic field in interplanetary space.

Space weather and solar storms

Space weather refers to the environmental state in space around the Earth at an altitude higher than the ionosphere. When space weather disturbances are severe, not only are astronauts in space exposed to radiation and the operation of artificial satellites affected, but also wireless communication and positioning using global positioning systems (GPSs) on the ground are disrupted. In some cases when space weather disturbances become very severe, the level of radiation exposure increases at the altitude of airplanes, and power grids on the ground are affected. As explained above, various technologies used in space are affected by space weather. Along with the rapid progress of space exploration, our social infrastructures have become increasingly dependent on the technologies used in space. Under such circumstances, the vulnerability of our society to changes in space weather has increased.

One phenomenon affecting space weather is solar wind, which is the flow of gas (plasma) emanating from the solar corona and blowing outward in all directions of interplanetary space. Depending on the structure of the solar magnetic field, two regions coexist in interplanetary space, i.e., a region where fast solar wind with a speed of up to 800 km/s blows and one where slow solar wind with a speed of 300–400 km/s blows. Because of the rotation of the Sun, the conditions of the solar wind reaching the Earth varies continuously, leading to changes in space weather.

Another phenomenon that causes greater disturbances in space weather is solar storms caused by explosions in the solar corona. So-

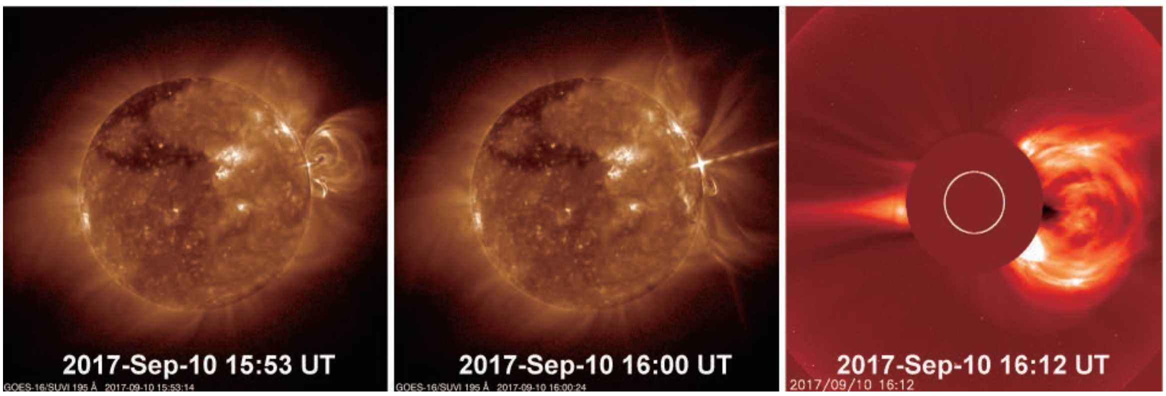

Figure 1 Solar storm on 10 September 2017. Solar corona (left, immediately before occurrence of solar flare; middle, immediately after the occurrence) observed by SDO (US) using extreme ultraviolet rays. right: CME observed using coronagraph on SOHO (US). The white circle at the center indicates the location of the sun.

lar storms cause (1) solar flares, in which corona gas is suddenly heated and has high luminosity (left and middle, Figure 1), and (2) coronal mass ejection (CME), which is a mass of corona gas ejected from the solar corona into interplanetary space at high speed (right, Figure 1). Associated with a powerful solar storm that occurred on 6 September 2017, increased positioning errors of GPSs were observed on the 8 September in Japan, which attracted public attention, and disturbances in telecommunication were also observed in the USA. In addition, another strong solar storm (Figure 1) occurred on 10 September 2017. Associated with the storm, it was estimated that the radiation dose absorbed by humans was only slightly increased at the altitude of airplanes over the polar regions (i.e., not harmful to human bodies).

Numerical simulation of propagation of solar wind and solar storms

It takes 1–5 days for CME generated at the solar corona to reach the Earth ~150 million kilometers away, while the occurrence of the solar storm can be observed as solar flares using electromagnetic waves (which take ~500 s to reach the Earth from the sun). Therefore, the observation of solar flares can be used in the prediction of the arrival of CME, the time of arrival, and its effects. If we can predict the arrival of severe CME immediately after a solar flare, we can take appropriate measures to mitigate the damage from the CME in advance.

One of the most important factors determining the impact of a CME is the magnetic field of the part of the CME that passes through the Earth. When the magnetic field of the CME has northward components, the Earth's magnetic field, the magnetosphere, serves as a barrier and prevents solar wind from penetrating the space around the Earth. However, when the magnetic field of the CME has southward components, the barrier function of the Earth's magnetosphere is weakened. Therefore, the energy of the solar wind flows into the magnetosphere, causing a significant disturbance. As explained, predictions of the direction of the CME magnetic field as well as the energy density of the CME are important.

Our research group has developed a simulation model (SUSANOO-CME) that can simulate three-dimensional interplanetary space in which realistically distributed solar wind blows and the propagation processes of CMEs and their internal magnetic fields using the observation data of the sun and coronagraphs. In SUSANOO-CME, the propagation processes of the CME and magnetic field are simulated assuming that CMEs are ejected radially outward from the corona where solar flares occur.

We succeeded in simulating both the speed of gas reaching the Earth and the southward magnetic field for the solar storm that occurred during 28–30 October 2003, which was the strongest solar storm of this century, by inputting the observation data of 22 solar storms collected between late October and the beginning of November 2003 (Figure 2).

Real-time prediction of the effects of solar storms

Space Environment Laboratory monitors and predicts the states of the sun, magnetosphere, and ionosphere every day and issues a space weather forecast to the public. The impacts of solar storms are predicted on the basis of past statistical data; thus far, prediction has not been carried out by numerical simulation, in contrast to terrestrial weather forecasts.

To successfully predict the impacts of solar storms by numerical simulation, our research group is developing a simulation system for prediction using real-time measurement data of the sun (Figure 3). The system automatically collects data observed by spacecraft, Geostationary Operational Environmental Satellite (GOES), Solar Dynamics Observatory (SDO), Solar and Heliospheric Observatory (SOHO), and Solar Terrestrial Relations Observatory (STEREO) managed by the US and analyzes the data. The forecasters carry out analyses difficult to automate, such as measurement of the propagation speed of CME, on the browser of the system. In addition, some parameters cannot be estimated from the measurement data. Therefore, simulation for several cases with different parameter values is carried out to comprehensively evaluate the results of all the cases and predict the changes in corona gas and magnetic field that will reach the Earth in the next seven days.

Currently, the trial operation of a prototype system is being carried out. We hope that one of the simulation results will accurately reproduce the corona gas and the magnetic field reaching the Earth; however, correct reproduction is still difficult. Through future improvement of the system, we plan to find the appropriate combination of parameters that can accurately reproduce the changes in the corona gas and the magnetic field reaching the Earth. In addition, we plan to develop a method that gives the prediction as probabilistic information, i.e., which result is most likely to occur among several simulation results.

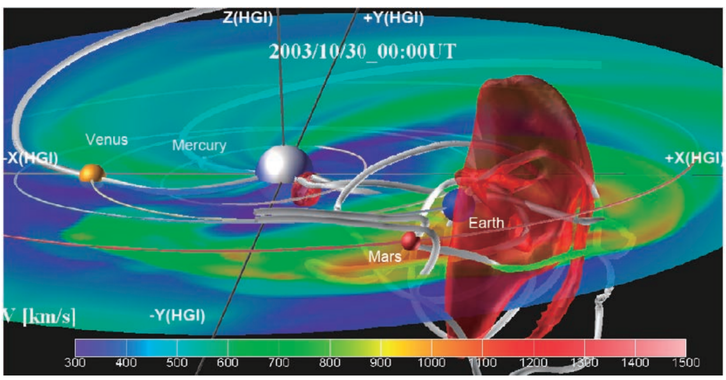

Figure 2 Flow and magnetic lines of solar wind and CME when a CME passes through the Earth. The background color indicates the speed of the gas. High-speed gas in the front part of CME (1,200 km/s, red equivalent face) and the lines of magnetic force inside it.

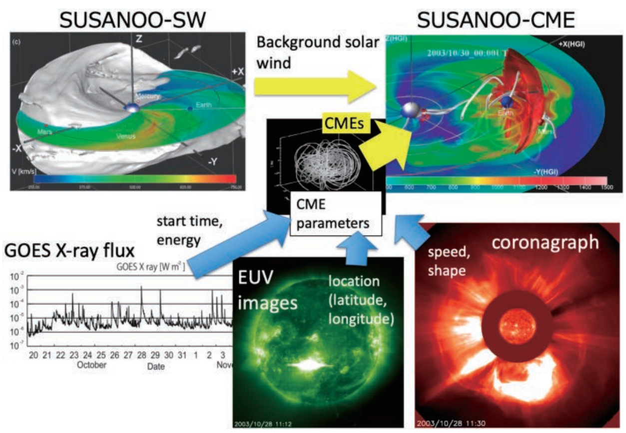

Figure 3 Outline of system for predicting the effects of solar storms using SUSANOO

Space Weather Forecast

NICT public information service

KUBO Yûki
Research Manager
Space Environment Laboratory
Applied Electromagnetic Research Institute

He joined Communications Research Laboratory (current NICT) in 1998 after receiving a degree of MSc in astronomy. He has worked for a research on space weather forecasting such as a solar radio observation and cosmic rays, and has also managed space weather forecast operation. Ph.D.

Space weather forecasting is currently a hot topic. This expression may reflect the current state of space weather. Although you may not be familiar with space weather, the demand for information on space weather, including forecasts and alerts issued, has rapidly increased. Information on space weather has started to be used for the operation of commercial airplanes. In addition, the use of space weather information in various fields such as wireless communication and positioning using satellites is being actively discussed.

History of space weather forecasting

NICT has been involved in providing radiowave propagation alerts to inform users in advance of possible shortwave communication failures since the early 1950s when the Radio Research Laboratory of the Ministry of Posts and Telecommunications (the predecessor of NICT) was launched (Figure 1). The range of the service was extended to include forecasting and issuing of alerts related to solar activities and geomagnetic disturbances that may cause shortwave communication failures in 1988, when the Radio Research Laboratory changed its name to the Communications Research Laboratory. Around the same time, the word "space weather forecasting" started to be widely used around the world.

The range of the space weather forecast service provided by NICT has since been further expanded to forecasting and issuing of alerts related to shortwave communication failures, solar activities that may cause such failures, geomagnetic disturbances, the Dellinger phenomenon, radiation belt electron conditions that may cause the malfunction of artificial satellites, solar energetic particle conditions that may have an adverse effect on the health of aircrews exposed to their irradiation, and ionospheric disturbances that may cause errors in positioning using satellites. The information is distributed daily to users via e-mail and the website of the NICT space weather forecast center. In addition, the Space Weather User's Forum and Space Weather User's Council Meeting are held every year to promote the use of space weather information and exchange opinions with users.

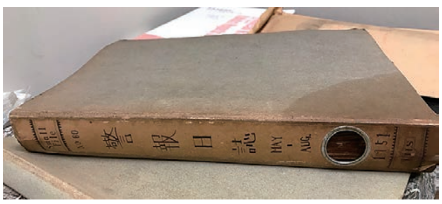

Figure 1 Record of radiowave propagation alert service (1951)

Development of space weather forecast

In early September 2017, the sun produced a significant solar flare (an explosion on the solar surface) for the first time in approximately 11 years, which caused major disruptions to society. The Geospatial Information Authority of Japan of the Ministry of Land, Infrastructure, Transport and Tourism reported that there were time slots when the positioning accuracy of global positioning systems (GPSs) was very low. With this report, people recognized that events associated with space weather may affect our daily activities.

After the occurrence of damage caused by changes in space weather, the necessity and importance of space weather forecasting were focused on and, as a result, the environment around the space weather forecast service in Japan dramatically changed. The space weather forecast service had been entirely carried out at the head office of NICT located in Koganei (Tokyo). With the recognition that the space weather forecast service should continue even when the functions of the head office may be suspended owing to disaster, a branch of the Space Weather Forecast Center was established in the premises of the Advanced ICT Research Institute of NICT located in Kobe, in March 2019 (Figure 2). The branch currently has no staff; however, systems required for the space weather forecast service have already been installed in preparation for emergencies involving the

NICT head office. When disruption caused by changes in space weather occurred in September 2017, in addition to the media, NICT received many inquiries from the public both day and night. Therefore, the necessity of 24-hour operation of the space weather forecast service was recognized anew, and 24-hour operation was launched in December 2019.

■Providing information to International Civil Aviation Organization

The International Civil Aviation Organization (ICAO) is concerned about the effects of space weather phenomena on the operation of airplanes from the following three viewpoints: (1) shortwave communication failures and failures of radiowave communications via artificial satellites between an airplane and flight control on the ground, (2) increased measurement errors in airplane positioning related to electronic navigation, and (3) exposure of aircrews to cosmic rays.

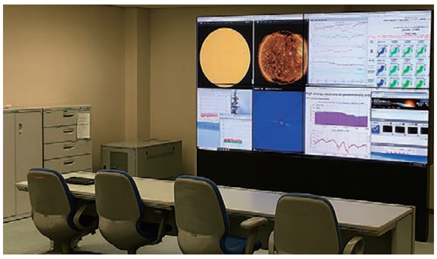

Figure 2 Substation of Space Weather Forecast Center in Kobe

As a member of the ICAO Global Space Weather Center, NICT has been providing information on shortwave communication and positioning by satellite. In addition, NICT has developed a warning system for aviation exposure to solar energetic particles (WASAVIES, Figure 3) to provide information on space radiation (refer to the article below on the ICAO Global Space Weather Center).

■Future prospects of space weather forecast service

As explained above, the space weather forecast service of NICT has been widely recognized as a public service provided by NICT. The importance of the service is increasing. Another important mission of NICT is to carry out research to improve the accuracy of forecasts. Through the research-to-operation and operation-to-research (R2O2R) approach, by which the achievements of research and development are used in the space weather forecast service and the issues arising in the operation of the space weather forecast service are provided as feedback to research and development, we will be able to serve as a bridge between research and operation. We believe that it is very important to further develop our space weather forecast service to increase its utility to the public.

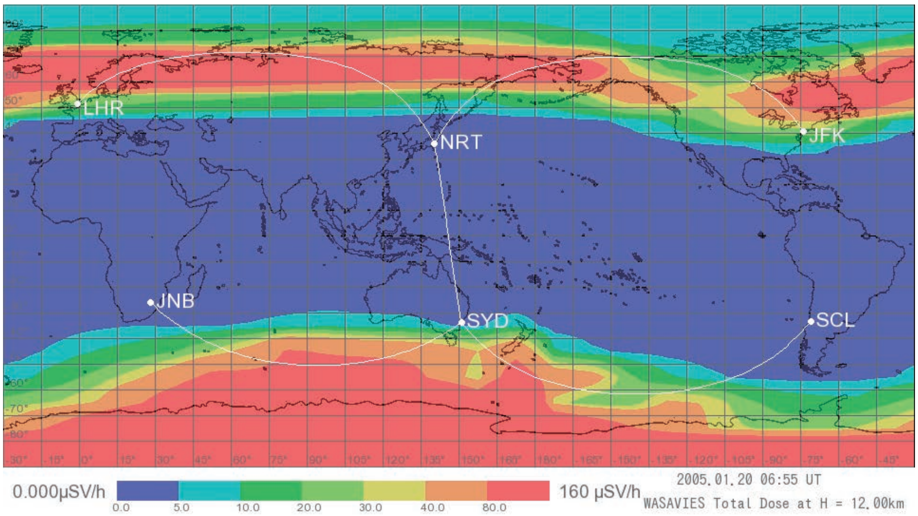

Figure 3 Example of radiation dose rate map estimated using WASAVIES

ICAO Global Space Weather Center

The opening ceremony of the ICAO Global Space Weather Center

On 7 November 2019, a United Nations specialized agency, ICAO, began the use of a designated space weather information service for the operation of commercial airplanes. ICAO recognized the importance of space weather forecasting in the operation of commercial airplanes from the following three viewpoints: (1) to avoid shortwave communication failures and failures of radiowave communications via artificial satellites between an airplane and flight control on the ground, (2) to suppress measurement errors in airplane positioning related to electronic navigation, and (3) to reduce the exposure of aircrews to cosmic rays. Three organizations, i.e., the Space Weather Prediction Center (SWPC) in the US, the Pan-European Consortium for Aviation Space Weather User Services (PECASUS) in the European Union, and the Australia, Canada, France and Japan (ACFJ) Consortium, were designated as the members of the ICAO Global Space Weather Center after an audit by the World Meteorological Organization (WMO), which is a United Nations specialized agency, during the period from January to March 2018. NICT is a member of the ACFJ Consortium and plays an active role in the ICAO Global Space Weather Center. The opening ceremony of the ICAO Global Space Weather Center was held on 7 November 2019.

The information on shortwave communication, satellite communication, positioning by satellite, and space radiation is provided to aviation-related organizations in a predetermined form called an advisory through a network of meteorological information. In the conclusive advisory disseminated by the ACFJ Consortium, an advisory on shortwave communication disseminated by the Bureau of Meteorology (Australia) and an advisory on satellite positioning and space radiation disseminated by Météo France (France) are included. (Note that no advisory on satellite communications is currently provided.) NICT provides data, such as measurement data and the results of model calculations, that are used to prepare the conclusive advisory. Because of NICT's historical background, i.e., the development of its space weather forecast service from its radiowave propagation alert service, NICT can provide information on not only shortwave communication and positioning by satellite but also space radiation, which is relevant to the former two. Therefore, NICT provides information based on the three viewpoints that are the focus of ICAO.

written by KUBO Yûki

Space Weather Forecasting Using AI Techniques

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In modern society, space utilization and information and communication technology (ICT) have become advanced. X-rays and high-energy particles emitted from solar flares and phenomena such as magnetic storms have impacts on our society. The sun emitted a large solar flare in September 2017 for the first time in 11 years, which grabbed the headlines.

The monitoring of solar flares has more than 100 years of history. These days, we can realize the continuous and highly resolved observation of the solar corona and the state of the magnetic field around sunspots using the solar observation satellites "Hinode" and "Solar Dynamic Observatory (SDO)." Our research goal is to forecast solar flares and space weather with high accuracy using the data obtained.

The conventional empirical forecast of solar flares was carried out manually on the basis of the classification of the shape of sunspots. However, the forecasting accuracy of this method was approximately 30–50%. We have endeavored to improve the forecasting accuracy by applying deep learning methods, which have drawn considerable attention in recent years, to the forecasting of solar flares. Huge amounts of data that have not been processable manually thus far are analyzed in real time by applying deep learning techniques for use in forecasting.

The "Deep Flare Net" model that we have developed can forecast the probability of solar flares occurring within 24 hours for each sunspot (Figure 1). By analyzing the features of sunspots detected in images of the sun, the model alerts users of an increased risk when sunspots with similar features to those that emitted solar flares in the past appear. Using approximately 300,000 images obtained by the SDO, our research group extracted 79 physical features on the basis of the past experience of forecasting and solar research, and the model learned these features. As a result, we succeeded in improving the forecasting accuracy to higher than 80%.*[1,2]

In April 2019, the forecasting website of Deep Flare Net (Figure 2) was launched. Depending on the probability of the occurrence of solar flares, one of three alert marks, "danger," "warning," and "quiet," is shown on the top page of the website, similar to the "sunny," "cloudy," and "rainy" marks of weather forecasts, so that nonprofessional users can easily understand the forecast. In addition, the probability of the occurrence of solar flares classified by their size is shown for each sunspot in as a graph. We are planning to improve our model on the basis of comments from users who visit the website.

When the Earth is irradiated with X-rays and ultraviolet emissions from solar flares, communication trouble and an increased error in satellite positioning may occur. In addition, as a result of the expansion of the atmosphere caused by solar flares, the orbits and the lifetimes of artificial satellites are sometimes affected.

In future studies, we plan to contribute to society by helping new space businesses through the use of AI techniques in forecasting the effects of solar flares on communication and positioning services that are indispensable in our daily lives and by improving the efficiency of the operation of satellites and airplanes. We will lead the technical innovation using technologies related to space and ICT technologies.

References
*1 Nishizuka et al. 2018 Astrophys. J. 858, 113
*2 Nishizuka, The Astronomical Herald, 112, 6 (in Japanese).

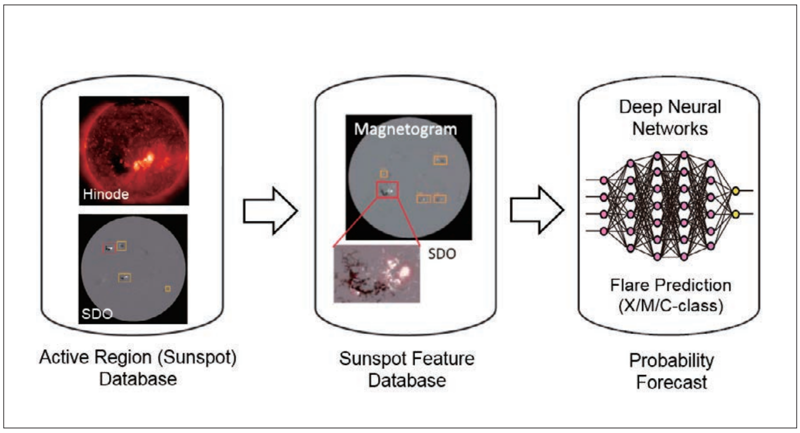

Figure 1 Outline of Deep Flare Net Model

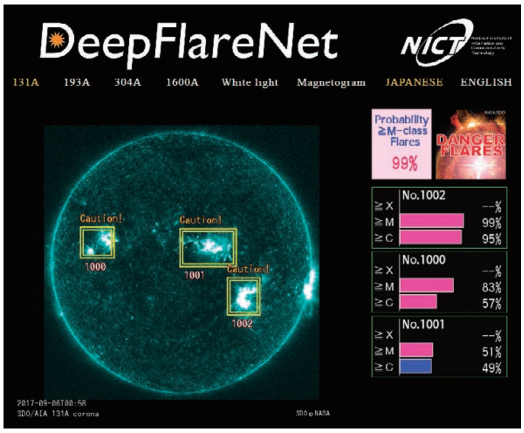

Figure 2 Screen shot of webpage of Deep Flare Net (https://defn.nict.go.jp)

NISHIZUKA Naoto

After graduating from graduate school, he worked at JAXA, NAOJ, and UCL/MSSL. Entered NICT in 2014. Engaged in R&D in solar physics and space weather forecast. Ph.D. (Science).

Development of Space Weather Forecasting System

—Approach from Model of Atmosphere and Ionosphere—

TAO Chihiro

Tenure-track researcher
Space Environment Laboratory
Applied Electromagnetic Research Institute
Ph.D. (Science)

Biography

2004 Graduated from Department of Geophysics, Tohoku University
2009 Received Ph.D. from Graduate School of Science, Tohoku University
2015 Joined NICT after serving as a project researcher at Japan Aerospace Exploration Agency and after finishing a postdoctoral fellowship in The Research Institute in Astrophysics and Planetology (IRAP), France, supported by Japan Society for the Promotion of Science
2017– Current position

Awards, etc.

2019: Young Scientist Award, Commendation for Science and Technology by the Ministry of Education, Culture, Sports, Science and Technology

Q&As

Q What do you like the most about being a researcher?

A I enjoy enriching my knowledge through practice. I would like to serve others through contributing to the scientific knowledge of humankind, even if only on a small scale.

Q What are you currently interested in outside of your research?

A Preparation of baby food for my daughter. I'm surprised by the different characteristics of food ingredients; for example, when grated a hard lotus root becomes sticky. I also enjoy seeing the reaction of my daughter when she tastes it.

Q What advice would you like to pass on to people aspiring to be researchers?

A Please devote yourself to what you are interested in, be stimulated while gaining a wide perspective, and push forward with a positive and resilient spirit.

Communication and positioning information has been used in various applications from maps for smartphones to aviation operations. Furthermore, it will be used in near-future technologies including automated driving and home delivery. In addition, information on the surrounding atmosphere is indispensable for the operation of artificial satellites orbiting near the Earth, including small satellites with increasingly diverse functions, and the understanding of the orbit of space debris that may damage satellites. Variations in the upper atmosphere may cause the failure of communication and positioning equipment and the operation of satellites; therefore, the understanding of the variations in the upper atmosphere is practically important.

Complicated variations in the upper atmosphere are induced as a result of multiregional factors, namely, (1) the disturbance and propagation of atmospheric waves from the lower atmosphere, (2) the interaction between the neutral atmosphere and the ionized atmosphere (ionosphere), and (3) energy inflow from the magnetosphere around the Earth.

Ground-to-Topside Model of Atmosphere and Ionosphere for Aeronomy (GAIA) is an effective tool for reproducing and predicting the variations in the upper atmosphere. GAIA is the first physical model that succeeded in covering regions from the surface of the Earth to the upper atmosphere without boundaries, including the interaction between the neutral atmosphere and the ionized atmosphere. Utilizing my research experience on the planetary environment before joining NICT, I have been making improvements to GAIA so that it can include the disturbance caused by the sun and the magnetosphere.

Currently, I am involved in the real-time trial calculation of space weather forecasting for several days ahead to practically apply GAIA to space weather forecasting. The goal of my study is to improve the accuracy of forecasting under the constraint of the insufficient available data. The output from GAIA is physical parameters such as density and wind velocity. Our research group is also developing indices from GAIA outputs that can be used to evaluate the effects on practical communication and positioning. We are also examining the use of GAIA outputs in other application models.

We hope that GAIA can function for space weather similarly to the meteorological model for weather forecasting.

Supercomputer for GAIA calculation at NICT

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