COMMISSION G: Ionospheric Radio and Propagation (including ionospheric communications and remote sensing of ionised media) (November 2016 – October 2020)

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1. Summary

URSI Commission G aims to discuss radio and its propagation in the ionosphere. In addition to these essential purposes, this commission is to study the ionospheric communications and remote sensing of the ionized media, too. The last purpose includes general research of the ionosphere and/or the upper atmosphere. We should note that measurement techniques and instruments take important part of our research in the commission G.

The ionosphere that overlaps with the upper atmosphere is the transition region from the Earth's atmosphere to the space. It is a region that is largely affected from both the top and bottom, and complex interactions occur. Recently, studies of the other planets are getting more important in our research community. Researchers from Japan contribute the vast research area of the USRI Commission G in wide spectrum. Level of the research is also very high. We have variety of measurement instruments on the ground, sounding rocket, and satellites. Region of the studies spreads from Japan, Asia to the world as well. We have big efforts on modeling (large-scale computer simulation) and database. Comprehensive analyses of multiple data are also actively conducted.

This report compiles contributions from our committee members. We summarize the research activities by showing major measurement instruments, observation network, related model/database projects, and future plans that are closely related to the Commission G. We also tried to include URL to many of our web pages, which we hope to be useful to interested readers. Following are the contents of our report.

2. Activity Report

2.1 Instruments and measurement techniques

2.1.1 PANSY

PANSY (Program of the Antarctic Syowa MST/IS Radar) is a project which was started in 2000 to comprehensively study the polar atmosphere with a large aperture atmospheric radar as the main instrument combined with complementary observation techniques and also with numerical modeling and theoretical works. (PANSY project web page: http://pansy.eps.s.u-tokyo.ac.jp/en/)

Continuous full system observation (with 520 kW transmitting power and 1045 array antennas) of the PANSY radar started late September 2015 and is ongoing until 2020. It enables us to capture various temporal- and spatial-scale phenomena in the Antarctic troposphere, stratosphere, mesosphere, and thermosphere/ionosphere with high temporal and vertical resolution throughout the year and to contribute to improving global climate models for better understanding of future climate change.

In addition, the first international campaign based on a combination of GCM (General Circulation Model) simulations and simultaneous observations by several MST/IS radars over the world including PANSY and some complementary instruments such as MF (Medium Frequency) and meteor radars, lidars, imagers, and so on was successfully conducted in the winters of 2017, 2018, 2019, and 2020. This campaign was named the Interhemispheric Coupling Study by Observations and Modeling (ICSOM: see details at http://pansy.eps.s.u-tokyo.ac.jp/icsom/), and approved as a project for ROSMIC (Role Of the Sun and the Middle atmosphere/thermosphere/ionosphere In Climate) of SCOSTEP (Scientific Committee on Solar-Terrestrial Physics) under ICSU (International Council for Science). It is expected that these international collaborations including the PANSY radar will promote a more accurate understanding of the Antarctic atmosphere and interhemispheric coupling processes.

2.1.2 EISCAT radar

NIPR (National Institute of Polar Research) and Institute of Space-Earth Environmental Research (ISEE), Nagoya University have joined the EISCAT (European Incoherent Scatter) Scientific Association since 1996 and conducted observations with three incoherent scatter radar systems, at 224 MHz, 931 MHz in Northern Scandinavia and one at 500 MHz on Svalbard. They kept high research activity in this period. Examples of research results are as follows. (EISCAT webpage in NIPR: http://eiscat.nipr.ac.jp/)

Ogawa et al (2019) studied data from the EISCAT radars above Tromsø and Longyearbyen between 1996 and 2015, and investigated how velocity and flux of ionospheric ion upflows vary during magnetic storms driven by corotating interaction regions (CIRs) and coronal mass ejections (CMEs). In the daytime, substantial ion upflows last for a few days after the storm onsets under small CIR storms, whereas they last for only a day under small CME storms. Kawamura et al (2020) studied the lifetime of O(1S) using the EISCAT UHF radar above Tromsø and a ground-based five-wavelength photometer to reveal the emission altitude of pulsating aurora (PsA). The emission altitude becomes lower in the morning side than in the midnight sector, which indicates that the energy of PsA electrons is higher in the later Magnetic local time (MLT) sector. Takahashi et al (2019) studied relationship between the motion of auroral patches and the polarization electric field generated therein observed with EISCAT radars, Kilpisjärvi Atmospheric Imaging Receiver Array (KAIRA), and an all-sky imager. The electron density and the height-integrated Hall conductance between 80 and 120 km were enhanced by a factor of 2–4 inside the auroral patches. Enhanced ion velocities due to the polarization electric field was also observed in the auroral patches at up to 200-km altitude.

2.1.3 SuperDARN Hokkaido East / West Radars

SuperDARN (Super Dual Auroral Radar Network) is an international collaboration project by more than ten countries in the world. In its initial stage, most SuperDARN radars have observed the polar regions higher than 60 geomagnetic latitude until 2004. The mid-latitude SuperDARN radars began operation in 2005, and several discoveries have been made using newly constructed SuperDARN radars by several countries in the world such as Japan, USA, UK, Australia and China. The Hokkaido East / West radars were constructed by Nagoya University in 2006 / 2014, and are located in the lowest latitude of the recently constructed radars. Detailed information on these radars is found from: http://cicr.isee.nagoya-u.ac.jp/hokkaido/index.html

The radars are used for a variety of studies of the magnetosphere and the ionosphere. In January 2017, an international workshop on the review of the accomplishment of the mid-latitude SuperDARN was held in Nagoya University. 15 participants from 5 countries intensively discussed accomplishments and future directions of the mid-latitude SuperDARN network. About two years later, a review paper on the mid-latitude SuperDARN was published in the Progress in Earth and Planetary Science (Nishitani et al., 2019, https://doi.org/10.1186/s40645-019-0270-5). The paper consists of 5 scientific sections (convection, ionospheric irregularities, HF propagation, ion-neutral interaction, and MHD waves), followed by the discussion of future directions.

2.1.4 MU radar

The MU radar is the 46.5-MHz atmospheric radar located in Shigaraki, Shiga, Japan. The radar can measure atmospheric winds from near the surface to about 20km, and is also useful to measure coherent and incoherent scatters from the ionosphere. Multi-beam capability with the active-phased array antenna is the most power feature of the system, and the various interesting observations were conducted so far. (MU radar and EAR web: http://www.rish.kyoto-u.ac.jp/mu+ear/english/index.html)

IEEE, an association dedicated to advancing innovation and technological excellence for the benefit of humanity, is the world's largest technical professional society. IEEE established the Milestones Program in 1983 to recognize the achievements of the Century of Giants who formed the profession and technologies represented by IEEE. Each milestone recognizes a significant technical achievement that occurred at least 25 years ago in an area of technology and having at least regional impact. In December 2014, IEEE decided to award Milestone to the MU (Middle and Upper atmosphere) radar as the first large-scale MST (Mesosphere, Stratosphere, and Troposphere) radar with a two-dimensional active phased array antenna system. The MU radar was established in 1984 by Kyoto University with collaboration of Mitsubishi Electric Corporation, and enabled continuous and flexible observation of the atmosphere, and has contributed to the progress of atmospheric science and radar engineering. Its dedication ceremony was successfully held on May 13, 2015 at Shirankaikan, Kyoto University.

Recent topic of the MU radar is the combination of its radar range-imaging observations of the turbulence and the direct measurement of the atmospheric parameters by using UAV. Scientists from USA and France conducted the observation campaign experiments.

MU radar web: http://www.rish.kyoto-u.ac.jp/mu/en/

2.1.5 Equatorial Atmosphere Radar

Equatorial Atmosphere Radar (EAR) is a big atmospheric radar located in West Sumatra, Indonesia. The EAR was established in June 2001, and has continued long-term observations since June 2001. Research Institute for Sustainable Humanosphere (RISH), Kyoto University and National Institute of Aeronautics and Space (LAPAN) of Indonesia jointly operate the facility that is open to scientists from both countries and from the world. The EAR data are basically opened.

Recent research topic is the joint experiment with EAR and the ultra long-duration balloon campaign that is named Stratole-2. Stratole-2 is a project to fly super pressure balloon around the equatorial region at an altitude of 18-20 km. Its first flight tests were conducted in 2019 and we joined the experiment by providing the EAR data. Data analysis from the experiment is underway.

EAR web: http://www.rish.kyoto-u.ac.jp/ear/index-e.html
Stratolle-2 project web: https://strateole2.cnes.fr/en/strateole-2-0

2.1.6 Ground-based network observations

MAGDAS

MAGDAS is the world network of magnetometer developed and maintained by International Center for Space Weather Science and Education (ICSWSE), Kyushu University. MAGDAS network and its observations are well maintained during this period. Since 2016, new observations started at 10 stations in Malysia, Sri Lanka, Peru. One FM-CW radar started observation of the ionosphere from Huancayo in Peru. Many studies of atmospheric tides, sudden stratospheric warming, various ionospheric phenomena, and thermosphere-ionosphere coupling are published in international journals. Number of MAGDAS related publications is 122 during 2016-2020.

MAGDAS related database web: http://data.icswse.kyushu-u.ac.jp/

PWING Project

The PWING stands for "study of dynamical variation of Particles and Waves in the INner magnetosphere using Ground-based network observations." The PWING project started on April 2016 as a 5-year project of the Grant-in-Aid for Specially Promoted Research of the Japan Society for the Promotion of Science (JSPS) (16H06286). The PWING project deploy OMTIs all-sky cooled-CCD airglow imagers, 64-Hz sampled induction magnetometers, 40-kHz VLF receivers, and 64-Hz riometers at 8 stations at magnetic latitudes of ~60 degree around the north-pole to cover longitudinal variation of aurora and electromagnetic disturbances in the inner magnetosphere. About 200 journal papers have been published related to this project.

PWING web: https://www.isee.nagoya-u.ac.jp/dimr/PWING/en/

ISEE Magnetometers

ISEE, Nagoya University is conducting the ISEE magnetmeter network in order to investigate the Pc1 pulsations and geomagnetic field disturbances. The network is expanding now and reaches more than 15 stations from the equatorial to the polar regions. New induction magnetometers at subauroral latitudes are deployed by the PWING project in 2017-2018. Various results has been obtained using these imagers, including propagation of Pc1/electromagnetic ion cyclotron (EMIC) waves near the plasmapause from the magnetosphere to the ionosphere and interaction of EMIC waves with ring-current ions to cause isolated proton aurora at subauroral latitudes. The digital data in CDF format are available via the ERG science center.

ISEE Magnetometers web: https://stdb2.isee.nagoya-u.ac.jp/magne/

VLF/ELF

Institute for Space-Earth Environmental Research (ISEE), Nagoya University has operated nine VLF/ELF receivers at subauroral latitudes and in Japan. The receivers at subauroral latitudes are deployed by the PWING project in 2017-2018. They are 40-kHz sampling continuous waveform measurements. Various results on the magnetospheric VLF/ELF waves, such as chorus and quasi-periodic emissions, has been reported recent years, including their longitudinal extent and magnetosphere-to-ground propagation. The spectral data are available via the ERG science center. The raw waveform data are also available upon request.

ISEE VLF/ELF web: https://stdb2.isee.nagoya-u.ac.jp/vlf/

AVON (Asia VLF Observation Network) group has been making continuous measurements of LF/VLF/ELF waves at Tainan (Taiwan), Saraburi (Thailand), Pontianak (Indonesia), Los Banos (Philippines), and Hanoi (Vietnam) since December 2007. 14 Universities/institutes including Chiba, Hokkaido, Tohoku Universities and Ashikaga Institute of Technology participate in the AVON project. The antennas consist of a monopole antenna, a dipole antenna, and an orthogonal loop antenna. The sampling frequency of LF/VLF transmitter signals is 200 kHz, while that of VLF/ELF waves radiated from lightning discharges is 100 kHz. Recently, the first observation of about 100-s periodic oscillations of intensity and phase in two LF transmitter signals over Japan at 05:52-05:56 UT on March 11, 2011 (about 5' 42" after the main shock onset the M9.0 earthquake) was reported. The 100-s LF periodic oscillation was caused by the vertical propagation of the acoustic waves excited by the seismic Rayleigh waves. Tohoku University group is also operating LF/VLF transmitter observation at Ny-Alesund (Norway), Poker Flat (Alaska), Athabasca (Canada), Zhigansk (Russia) to detect energetic electron precipitation from inner magnetosphere. These observations are a part of the ground-based observation networks for the ERG satellite launched on December 20, 2016.

New digital receiver for HF Doppler sounding

The University of Electro-Communications (UEC) has promoted HFD sounding in Japan. Now, four research institutes (Chiba University, Kibi International University, Nagoya University, National Institute of Technology, Kitakyushu College) have been cooperating to continue the observations. Due to the decrease of people who can handle analog circuits, it has become difficult to maintain existing analog systems. We have developed a digital HFD receiver system using SDR (Software-Defined Radio), which enables us to develop the receiver without the knowledge of the analog circuit devices. The new digital receiver is inexpensive and small. Therefore, we can easily deploy new receiving stations not only in Japan but in other countries. The dynamic range of the new receiver is wider (> 130 dB) than that of the previous system. The signal-to-noise ratio has also been significantly improved by 20 dB. The new digital receivers have been installed in seven stations of the HFD observation network (as of August 2021) and demonstrated the feasibility of SDR in actual ionospheric observations.

Project website: http://gwave.cei.uec.ac.jp/~hfd

VHF aeronautical navigation signals

University of Electro-Communications and other groups established a ground-based network of receivers of anomalous long-distance propagation of VHF aeronautical navigation signals (108-118 MHz). They were able to image the locations of the sporadic E (Es) layer by mapping the reflection points of the signals of which source were identified according to the information published for aeronautical operations. It was found that the anomalous propagation in the VHF navigation band occur quite frequently, sometimes the strength can be higher than the limit required for airborne receivers to work properly, and in some special cases it could be stronger than those from nearby stations. The results were reported to International Civil Aviation Organization (ICAO), and next update of an ICAO manual on aeronautical radio frequency spectrum will include the anomalous propagation effects on aeronautical navigation signals.

Reference: Hosokawa, K., J. Sakai, I. Tomizawa, S. Saito, T. Tsugawa, M. Nishioka and M. Ishii, A monitoring network for anomalous propagation of aeronautical VHF radio waves due to sporadic E in Japan, Earth, Planets and Space, 72, 2020.
Project website: http://gwave.cei.uec.ac.jp/cgi-bin/vor/vhf.cgi

Airglow imagers

ISEE, Nagoya University is conducting the Optical Mesosphere Thermosphere Imagers (OMTI) in order to investigate the dynamics of the upper atmosphere through nocturnal airglow emissions. The network is expanding now and reaches more than 20 stations from the equatorial to the polar regions. The OMTIs consist of ~20 all-sky cooled-CCD imagers, 5 Fabry-Perot interferometers, 3 airglow temperature photometers, and 3 meridian-scanning photometers. They measure two-dimensional airglow images in the mesopauseregion and in the thermosphere, wind and temperatures in the lower thermosphere, and airglow rotational temperatures in the mesopauseregion.

The researcher group conducts a new project PWING (study of dynamical variation of Particles and Waves in the INner magnetosphere using Ground-based network observations) and establishes new observation sites (ground-based stations) at 8 locations in northern subauroral region.

OMTI web: http://stdb2.isee.nagoya-u.ac.jp/omti/
PWING web: https://www.isee.nagoya-u.ac.jp/dimr/PWING/en/

SEALION

SEALION is an ionospheric observation network in Southeast Asia to monitor and study the occurrence and growth of equatorial ionospheric disturbances, especially plasma bubbles. The network has been setup by National Institute of Information and Communications Technology (NICT) since 2003 and has been operated to date by NICT with an international effort by seven institutes in five Southeast Asian countries. SEALION is one of the few observation bases in the world that is unique in having conjugate observational points both in the northern and southern hemispheres and around the magnetic equator. In January 2020, a new VHF radar was installed in Chumphon, Thailand, close to the magnetic equator, which is expected to capture the whole picture of plasma bubble generation.

SEALION data web: https://aer-nc-web.nict.go.jp/sealion/

Planetary atmospheres

Tohoku University and related groups carried out campaign-based large telescope observations of planetary atmosphere and ionosphere. Using the infrared high-resolution spectrographs installed on big-telescopes, such as Subaru/COMICS and IRCS and NASA IRTF/CSHELL, and small-telescopes Tohoku-60cm and Tohoku-40cm telescopes at the summit of Haleakala, they reported Jupiter's infrared auroral and thermospheric emission (Sinclair et al., 2019, Kita et al., 2018, Watanabe et al., 2018), Venus's mesosphere (Takami et al., 2020), Pluto's atmosphere (Arimatsu et al., 2020), and long-term volcanic activity of Jupiter's satellite Io (Sakanoi et al., 2017). Nakagawa et al. (2016) reported the development of a new Mid-Infrared Laser Heterodyne Instrument (MILAHI) with >10^6 resolving power at 7–12 μm. These measurement techniques are applied to exoplanets (Ge et al., 2019).

They are also operating the large radio telescope (IPRT) at Iitate, Fukushima, and HF antennas to measure planetary and solar radio emission (Kaneda et al., 2018, 2017, Tsuchiya et al., 2019b, 2018c, Hans et al., 2018). IPRT is a ground-based VHF-UHF radio telescope developed by Tohoku University and operated since 2000. IPRT has two distinctive radio receivers; one is a low noise and quite stable receiver tuned at 325MHz and 785MHz, and another one is a 100-500MHz spectro-polarimeter, named AMATERAS (the Assembly of Metric-band Aperture TElescope and Real-time Analysis System). The former is mainly used for observing Jupiter's synchrotron emission with the sensitivity of 0.1Jy, and enables us to investigate dynamical variations of Jupiter's deep inner magnetosphere. The latter is used for observing solar radio bursts with 10ms accumulation time and 61 KHz bandwidth, and enables us to clarify various micro structure of wave-particle or wave-wave interactions generated in the solar corona region.

Spacecraft, space telescope and air plane measurement data were also used to understand atmospheres of Mars (Hisaki: Masunaga et al., 2020, 2017, MAVEN: Nakagawa et al., 2020a, 2020b, Yoshida et al., 2020, Jakosky et al., 2018, Terada et al., 2017, England et al., 2016, Medvedev et al., 2016, TGO/NOMAD: Aoki et al., 2019, Korablev et al., 2018, Vandaele et al., 2018, Mars Express: Aoki et al, 2018b, Wolkenberg et al., 2018, Noguchi et al., 2017, SOFIA: Aoki et al., 2018a), Juipiter (Hisaki: Hikida et al., 2020, 2018, Kimura et al., 2019, 2018, 2017, Kita et al., 2019a, 2019b, 2016, Koga et al., 2019, 2018a, 2018b, Tao et al., 2018, 2016, Tsuchiya et al., 2018b, Yoshikawa et al., 2017, Juno: Clark et al., 2018, Fletcher et al., 2017, HST: Grodent et al., 2018), and Mercury(Messenger: Aizawa et al., 2020a, 2019b, 2018, Milillo et al., 2020, Murakami et al., 2020) and Venus (Akatsuki: Nara et al., 2020, Sato et al., 2020, Iwagami et al., 2018, Ogohara et al., 2017, Satoh et al., 2017, 2016, Ueno et al., 2016).

Modeling studies were used to understand atmospheres of Mars (Kamada et al., 2020, Kuroda et al., 2020, 2019, 2016, Sakai et al., 2018, Terada et al., 2016).

Haleakala long-term monitoring data web: http://c.gp.tohoku.ac.jp/~pparc/data/hal/
IPRT data center web: https://pparc.gp.tohoku.ac.jp/research/iprt/
Radio wave data web: http://c.gp.tohoku.ac.jp/sakura/#data

2.1.7 GNSS receiver network

GEONET (GNSS Earth Observation Network System) is the GPS receiver network over Japan that is operated by Geospatial Information Authority of Japan (GSI). GEONET consists of 1,300 GPS or more stations. This is one of the largest GNSS network of the world, and the data of every 30s is opened to the public. GEONET web page (in Japanese) is, http://terras.gsi.go.jp/geo_info/geonet_top.html. GEONET is also used for ionospheric monitoring and research. Two-dimensional TEC maps over Japan have been provided routinely by NICT (https://aer-nc-web.nict.go.jp/GPS/DRAWING-TEC/). Real-time 3D ionosphere tomography with GEONET data (every 15 min, 6 min latency) has been operated since 2016 (https://www.enri.go.jp/cnspub/tomo3/). It is utilized for real-time regional HF propagation prediction called HF-START (HF Simulator Targeting for All-users' Regional Telecommunication). Since 2018, real-time rate-of-TEC index (ROTI) maps over Japan have been provided every 5 min by ENRI. One of the prominent outcome of the real-time ROTI mapping is the study of the Es layer (https://www.enri.go.jp/cnspub/susaito/rocket/recent_roti.html). Daytime Es layer can be detected by projecting ROTI values at an altitude of 100 km. Furthermore, characteristics of the Es layer such as orientation and propagation velocity can be estimated.

More application-oriented study is also important with the GNSS use for the ionosphere. ENRI is leading activities to characterize the spatial gradient in ionospheric TEC for aviation use of GNSS in a framework of ICAO Asia-Pacific region. Ionospheric TEC gradient data from States/Administrations in the Asia-Pacific region have been consolidated and a common "threat model" in the region for the ground-based augmentation system (GBAS) to enable precise approach guidance for airplanes has been established in 2016. Studies to improve the threat model as well as evaluation of TEC gradients of the background ionosphere are being conducted. Scintillation of GNSS signals are also of great interest for GNSS community. ENRI has been studying the ionospheric scintillation effects on GNSS signals from multiple constellations (GPS, GLONASS, Galileo, Beidou, QZSS etc.) and multiple frequencies (L1, L2, and L5) by using networks in southern Japan and Southeast Asia.

2.1.8 Satellite missions

During the period of 2016-2020, there are several satellite missions conducted by JAXA, and used for the studies of the ionosphere, magnetosphere and planetary sciences.

IMAP/VISI

Airglow emissions at the lower-thermosphere (O2 762 nm, 95km alt.) and the upper-thermosphere (O 630 nm, 250 km alt.) are measured with IMAP/VISI on the international space station (ISS). Many concentric gravity wave events in the O2 emission, and equatorial anomaly and plasma bubbles in O630 nm emission (Perwitasari et al., 2016, Nakata et al., 2018). Characteristics of mesospheric bore events were precisely examined using statistical data of O2 emission (Hozumi et al., 2019, 2018). Further, results from simulatnous measurements between IMAP/VISI and DNB was reported (Yue et al., 2019).

IMAP/VISI project web: https://www.iss-imap.org/

AKATSUKI

AKATSUKI, also known as the Venus Climate Orbiter (VCO) and Planet-C, is a Japanese (JAXA) space probe tasked to study the atmosphere of Venus (Sato et al., 2014, 2015). It was launched aboard an H-IIA 202 rocket on 20 May 2010. The spacecraft was successfully inserted into the Venus' orbit by the thrust ejection operation on December 7, 2015. After checking condition of the on-board instruments, scientific observations started in April 2016, and data analyses are now carrying out (Nara et al., 2020, Sato et al., 2020, Iwagami et al., 2018, Ogohara et al., 2017, Satoh et al., 2017, 2016, Ueno et al., 2016).

AKATSUKI mission web: http://www.isas.ac.jp/en/missions/spacecraft/current/akatsuki.html

HISAKI

HISAKI, also known as the Spectroscopic Planet Observatory for Recognition of Interaction of Atmosphere (SPRINT-A), is a Japanese ultraviolet astronomy satellite operated by JAXA. The first mission of the JAXA's Small Scientific Satellite program was launched in September 2013 on the maiden flight of the Epsilon rocket. HISAKI carries an extreme ultraviolet spectrometer which will be used to study the composition of the atmospheres and the behavior of the magnetospheres of the planets of the Solar System, such as Jupiter (Hikida et al., 2020, 2018, Kimura et al., 2019, 2018, 2017, Kita et al., 2019a, 2019b, 2016, Koga et al., 2019, 2018a, 2018b, Tanaka et al., 2018, Tao et al., 2018, 2016, Tsuchiya et al., 2018b, Yoshikawa et al., 2017, Juno: Clark et al., 2018, Fletcher et al., 2017, HST: Grodent et al., 2018) and Mars (Masunaga et al., 2020, 2017). Campaign-based collaboration with coordinated satellite measurements between Hisaki and other spacecraft, such as HST and Juno, carried out.

HISAKI mission web: http://www.isas.ac.jp/en/missions/spacecraft/current/hisaki.html

ARASE

ARASE, also known as Exploration of energization and Radiation in Geospace (ERG), is a scientific satellite to study the Van Allen belts. It was developed by the Institute of Space and Astronautical Science of JAXA. ARASE was launched aboard Epsilon launch vehicle at 11:00:00, 20 December 2016 UTC into apogee height 32250 km, perigee 214 km orbit. Subsequent perigee-up operation moved its orbit to apogee 32110 km, perigee 460 km of 565 minutes period. After initial checking for satellite and on-board instruments, JAXA confirmed that every function is working well. Nominal operation has been started in March 2017, and scientific results for pulsating aurora, characteristics of chrus waves and ECH waves in the magnetosphere, high-energy electron precipitations, and development of instruments and onboard software are reported in many papers (Colpitts et al., 2020, Fukizawa et al., 2020, Hosokawa et al., 2020, Inaba et al., 2020, Miyoshi et al., 2020, Kataoka et al., 2020, Martinez-Calderon et al., 2020, 2019, Masuda et al., 2020, 2018, Nose et al., 2020, 2018, Kasahara S. et al., 2020, 2018, Shiokawa et al., 2020, 2017, Teramoto et al., 2019, Hashimoto et al., 2018, Hikishima et al., 2018, Kato et al., 2018a, 2018b, Kasahara, Y. et al., 2018, Kazama et al., 2018, Kotov et al., 2018, Kumamoto et al. 2018, Nagatsuma et al., 2018, Ozaki et al., 2018, Shimbori et al., 2018, Shoji et al., 2018, Seki et al, 2018, Kasaba et all, 2017, Miyoshi et al., 2017). Related to high-energy electron precipitation which cause the ionization at the D-region altitude, ground-based radio observation data were reported (Hirai et al., 2018, Ohya et al., 2018, Tsuchiya et al., 2018).

ARASE mission web: http://www.isas.ac.jp/en/missions/spacecraft/current/erg.html

2.1.9 Sounding rocket experiments

JAXA/ISAS Sounding Rocket SS-520-3

The SS-520-3 sounding rocket will be launched from the Svalbard Rocket Range in Svalbard, Norway in 2021 to understand the acceleration mechanism of escaping ions from ionosphere in the cusp region. This rocket will reach over 800 km in order to observe in the dayside cusp region. EISCAT radar observation from the ground and optical observation will be simultaneously made, too. We will investigate the heating and acceleration mechanism of the particles by plasma waves which leads to the outflow of the ionized particles from the in-situ data obtained by this rocket experiment.

Rocksat-XN rocket

The Rocksat-XN rocket is an international student mission with participation from the US, Norway and Japan. RockSat-X student experiments are developed with an objective of providing students with an enhanced experience of flying experiments exposed to the space environment. The RockSat-XN mission was successfully launched from Andoya Space Center, Norway on January 13, 2019. Japanese group named PARM consists of ISAS/JAXA (high-energy electron, and magnetic field), Tohoku University (Auroral camera), University of Tokyo (medium-energy electron). The scientific purpose of PARM is to clarify microbursts (temporal precipitation of high-energy electrons) accoicated with pulsating aurora. They could observe electron precipitations although pulsating auroral emission was not observed. This project is evolvingly linked to the next rocket mission called LAMP which is scheduled to be launched in the winter of 2021.

Rocksat-XN web page: https://spacegrant.colorado.edu/national-programs/rocksat-xn

2.1.10 Instruments for planetary sciences

Now Japan operates three spacecrafts HISAKI, AKATSUKI and MIO for planetary sciences. In addition, researchers are using number of telescopes on the ground. JAXA recently started the future Mars Moon exploration project (MMX), which is going to observe Phobos, Deimos and Martian atmosphere, and some groups are joining in the core teams for science and instruments. Hokkaido University operates 1.6m Pirka Telescope that is dedicated for observations of planets (http://sana.ep.sci.hokudai.ac.jp/nayoro/index-en.html). This telescope joins “Optical and Infrared Synergetic Telescope for Education and Research (OISTER)” that networks telescopes of seven universities and National Astronomical Observatory of Japan (NAOJ) (Project web page: http://oister.oao.nao.ac.jp/ (in Japanese)). Tohoku University also plays an important role to study planets from the ground-based telescope. They were operating a 60-cm telescope (T60) dedicated for planetary observations at the summit of Haleakala (https://pparc.gp.tohoku.ac.jp/haleakala/). Visible chronagpraph imager, high-resolution Echellle spectrograph (VISP), and super-high resolution heterodyne spectrograph (MIHAHI) are installed on T60 (Sakanoi et al., 2017). They are also developing a near-infrared imager and Echelle spectrograph. Nakagawa et al. (2016) reports results for Venus atmosphere from this facility after relocation. As shown in the later section (G3.2), the research group is developing a 2-m telescope called PLANTES in the same location. The study of the planetary atmosphere is a hot topic in the research field and more data from Japanese satellites and ground-based telescopes are now expected.

2.2. Model, database, and multi-instrument analysis

2.2.1 GAIA

Ground-to-topside model of Atmosphere and Ionosphere for Aeronomy (GAIA) is a global physics model of the Earth's whole atmospheric regions from the troposphere to the topside thermosphere as well as the ionosphere. The model has been developed under the collaboration between Kyushu University, Seikei University and NICT since 2007, in aiming to understand the process of vertical coupling in the Earth's atmosphere both for the short and long terms, to understand the process of occurrence, growth and decay of upper atmospheric disturbances due to solar flares and magnetic storms, and to build a base model for numerical space weather prediction.

Some of the recent studies using GAIA can be found in the research of long-term vertical atmospheric coupling (Tao et al., 2017; Liu et al., 2017, 2020), equatorial ionospheric disturbances (Yamamoto et al., 2018; Shinagawa et al., 2018, 2020; Ghosh et al., 2020), and global magnetic field variations (Fujita et al., 2018).

GAIA project web: https://gaia-web.nict.go.jp/index_e.html

2.2.2. Numerical Simulations of Atmospheric Escape

Tohoku University group and related researchers have developed electromagnetic hybrid (particle ions/fluid electrons) and magnetohydrodynamic (MHD) simulation codes that comprehensively describe the interaction between the solar wind and the ionosphere of unmagnetized planets. They have been clarifying the physical mechanisms and pathways by which the ionized atmospheres of planetary origin removed into space. There simulation results are compared with satellite and spacecraft data and ground-based telescope data in which Tohoku University group leads or participates, in order to elucidate the ionization/neutral atmospheric escape and evolution of the atmosphere of Mars, Venus, and exoplanets, and to understand the conditions for the establishment of habitable planets.

2.2.3 IUGONET

Global phenomena observed in the Earth’s upper atmosphere are the results of many complex processes, such as the energy and momentum input from the Sun (e.g., solar radiation and solar wind), the energy and momentum transport by atmospheric waves from the lower atmosphere, and various internal phenomena (e.g., electromagnetic energy transport, plasma convection, chemical reaction). To understand the mechanism of the long-term variation in the upper atmosphere, therefore, it is important to analyze various data (e.g., wind velocity and temperature in the atmosphere, auroral images, geomagnetic field, solar activity index, etc.) obtained by the global ground-based network observation.

The Inter-university Upper atmosphere Global Observation NETwork (IUGONET) project started in 2009 (Abe et al., 2014; Yatagai et al., 2014, 2015). The objective of the project is to establish a metadata database of various ground-based observation data covering a wide region from the Sun to the Earth; this will encourage more studies on the mechanisms of long-term variations in the upper atmosphere. Also, they developped a software to ease comparison between various types of systems. IUGONET would be important for future study of complicated nature of the ionosphere.

Project web: http://www.iugonet.org/index.jsp?lang=en

2.2.4. Shortwave Propagation Simulator (HF-START) Service

To provide propagation information of the HF-band radio waves, the service of shortwave propagation simulator (HF Simulator Targeting for All-users' Regional Telecommnications; HF-START) has been started in cooperation with National Institute of Information and Communications Technology (NICT), Chiba University, and Electronic Navigation Research Institute, National Institute of Maritime, Port and Aviation Technology (ENRI). In this web site, users can calculate a propagation path between any two points. The three-dimensional ionospheric electron density distribution is necessary to calculate the propagation path. For the calculation of propagation paths in Japan, the electron density distribution derived by tomography using GNSS TEC data provided by ENRI is used. For the global propagation paths, we use the electron density distribution derived from the IRI model or GAIA simulation results. Since all the data of electron density are provided in almost real-time, propagation paths can be also determined in almost real time. By specifying the date and time, users can also calculate the propagation paths for any date and time in the past. HF-START has been featured in magazines and SNS for amateur radio operators, and improvements such as estimation of reception strength are expected in the future.

Website https://hfstart.nict.go.jp/

2.2.5. Studies of ionosphere/atmosphere vertical coupling

During this period, we have made two major progresses in understanding the vertical coupling processes in the Earth's atmosphere.

First, the thermosphere and ionosphere have been found to respond to the El-Nino Southern Oscillation (ENSO), with periodic changes in the thermosphere and ionosphere density. Using a series of model simulation, we have revealed the mechanism behind this to be mainly related to tidal modulations during ENSO. Particularly during the intense 2015/2016 ENSO event, our analysis shows large DW1 tidal enhancement with peak amplitude of 7.4 K (74%) higher than that under neutral (non-ENSO) conditions. For the first time, we successfully quantified the relative contribution of tidal generation and propagation to the observed tidal enhancement. The tidal generation via tidal heating is found to contribute 0.5 K (7%) of the enhancement, while tidal propagation contributes to the remaining 6.9 K (93%) of the enhancement. Our study further suggests that the overlapping of the 2015 El Niño with the eastward phase of the QBO induced the large enhancement of the DW1. These findings have been highlighted in AGU EOS news letter (Liu et al, 2017, Kogure & Liu 2021).

Second, we have mapped the global gravity wave distribution in the bottom ionosphere for the first time using LEO satellite observations. The analysis reveals pronounced features on their global distribution and seasonal variability: (1) A prominent three-peak longitudinal structure exists in all seasons, with stronger perturbations over continents than over oceans. (2) Their seasonal variation consists of a primary semiannual oscillations (SAO) and a secondary annual oscillation (AO). The SAO component maximizes around solstices and minimizes around equinoxes, while the AO component maximizes around June solstice. These GW features resemble those of EPBs in spatial distribution but show opposite trend in climatological variations. This may imply that stronger medium-scale GW activity does not always lead to more EPBs. Possible origins of the bottomside GWs are discussed, among which tropical deep convection appears to be most plausible. These findings have been picked up by newspaper (日刊工業新聞)

2.3. On-going and future plans

2.3.1 Masterplan 2014/2017/2020

Research Institute for Sustainable Humanosphere (RISH), Kyoto University, National Institute of Polar Research (NIPR), Institute for Space-Earth Environmental Research (ISEE), Nagoya University, and International Center for Space Weather Science and Education (ICSWSE), Kyushu University proposed the research project “Coupling process in the solar-terrestrial system” to the meeting. We study the solar energy inputs into the Earth and the response of Geospace (magnetosphere, ionosphere, and atmosphere) to the energy input by installing large atmospheric radars with an active phased array antenna at the equator and the Arctic regions. One is Equatorial MU (EMU) radar by RISH in Sumatera Island, Indonesia, and the other is EISCAT_3D by NIPR in northern Scandinavia under international collaborations. We also develop the global observation network that is jointly conducted by ISEE and ICSWSE. This project has been successfully selected as one of highest-priority projects in Masterplan 2014/2017/2020. We will keep applying this project to the SCJ Masterplan which next selection will be in 2023.

Project web: https://www.rish.kyoto-u.ac.jp/masterplan2020/

2.3.2 Telescope PLANETS

“PLANETS (Polarized Light from Atmospheres of Nearby ExtraTerestrial Systems)” is a project to develop a new telescope dedicated to the planetary science by the international collaboration by Tohoku University, University of Hawai'i Institute for Astronomy (IfA), the Kiepenheuer Institute for Solar Physics (KIS) and Universidade Estadual de Ponta Grossa (Sakanoi et al., 2018). The telescope is characterized by a high-contrast optical system provided by a low-scattering off-axis main mirror, adaptive-optics (AO), and stable atmospheric conditions of an observatory site at a high-altitude. The scattering light of PLANETS is estimated to be more than 10 times better than that of a normal large telescope. A major scientific target is to detect faint emissions of gasses erupted from Jovian satellites Io and Europa. Another major scientific target is the escaping gases surrounding planets. The project is now underway, and expects the first light in Japan in 2021, and this will be installed at Haleakala in 2022.

Project web: https://www.planets.life/planets-telescope/
http://www.ifa.hawaii.edu/haleakalanew/planets/

2.3.3. FACTORS

FACTORS stands for Frontiers of Formation, Acceleration, Coupling, and Transport Mechanisms Observed by the Outer Space Research System, which is going to be proposed as a next-generation multi-satellite formation flight mission now selected as the working group of ISAS/JAXA. Major scientific targets are: 1) energy transport in the magnetosphere-ionosphere (MI) coupling system and their relationship to small-scale auroral phenomena, 2) particle transport in the MI system by ion outflow, and 3) neutral-ion coupling in the auroral thermosphere. Multi-satellite observation of small-scale plasma parameters and simultaneous auroral imaging data in the altitude range from ~300 km to 4000 km enables us to understand dynamical spatial and time variations of Alfvenic wave acceleration, field-aligned current, particle distribution function and small-scale auroral emission. Related with this project, small-scale auroral dynamics using the past satellite missions and ground-based data were carried out (Nishimura et al., 2020, Fukuda et al., 2016, Nakamura et al., 2016, Sato et al., 2016)