# Commission H: Waves in Plasmas (November 2013 - October 2016)

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Based on the papers published from November of 2013 to October of 2016, we compiled major achievements in the field of plasma waves and related studies made by Japanese scientists and their collaborators. We collected published papers from the Japanese Commission H members and categorized them into three groups as shown in Contents.

## Contents

# H1. Space Observation and Experiment of Plasma Waves

## H1.1 Magnetospheric Plasma Waves

### <Akebono>

The Akebono was launched on February 22, 1989 and operated for 26 years. Its observation activities were terminated on April 23, 2015, due to deterioration of onboard instruments and reduced flight altitude after 26 years and two months of operation. Because of its unique orbit, it achieved various observation results not only in the auroral region but also in the radiation belt. Plasma wave instruments named VLF and PWS, and radiation monitor (RDM) were achieved regular data acquisition for 26 years and contributed important science output in the long-term periodical changes of the radiation belt.

Polarization reversal and mode conversion from R-mode to L-mode (and vice versa) of the waves in ELF range are important clue to derive ion constituents in the plasmasphere. Matsuda et al. [2014a] reported EMIC waves in the vicinity of the geomagnetic equator exhibiting a sudden decrease in intensity (characteristic lower cutoff) at just above half of the proton cyclotron frequency. The waves were observed during a magnetic storm in April 1989. They demonstrated that the waves propagate with a large wave normal angle with respect to the geomagnetic field line and that they had a crossover frequency above the characteristic lower cutoff. The waves were repeatedly observed within a half day after sudden decreases in Dst; however, they disappeared when the recovery of the Dst index became moderate. They suggested that wave generation appears to be closely correlated to fresh energetic particle injection, and that the existence of a few percent of M/Q=2 ions can explain the lower cutoff of the EMIC waves under the condition of multiple ion species.

Ion cyclotron whistler is left-handed polarized electromagnetic ion cyclotron mode wave converted from a lightning electron whistler. Matsuda et al. [2014b] introduced M/Q=2 ion cyclotron whistlers observed by Akebono in the altitude region around 3200–10000 km (L = 1.5–3.4). The observation point was a considerably higher altitude than those previously reported, that suggests M/Q=2 ions are present not only in the low-altitude region but also in the inner magnetosphere around L=3.4. Following this study, Matsuda et al. [2015] examined the spatial occurrence distributions of $H^+$, $He^+$, and M/Q = 2 ion band ion cyclotron whistler waves observed by Akebono below an altitude of 10,500 km. The statistical analysis showed that $H^+$ band ion cyclotron whistlers are rarely observed in the equatorial region, while M/Q = 2 ion band ion cyclotron whistlers are frequently observed. They proposed a model for generation of several bands of ion cyclotron whistlers along a propagation path. They also suggested density enhancement process of M/Q = 2 ions in the nightside plasmasphere. This kind of ion cyclotron whistler waves are also observed by Van Allen Probes [Matsuda et al., 2016], and their specific frequencies such as cross-over frequencies and lower-hybrid frequencies in the multicomponent ions could be important clue to derive ion constituent in the magnetosphere and plasmasphere.

The VLF instruments on board Akebono measures not only wave spectrum in digital format but also analogue waveform, and the analogue waveform data are transmitted via analogue telemetry. Huge amount of analogue data have been stored, but data analyses are not comprehensively performed so far because of the difficulties of their peculiar characteristics. Oike et al. [2014] statistically analyzed lightning whistlers detected from the analog waveform data using a newly developed data analysis system introduced by Kasahara et al. [2015]. Large amount of data from 1989 to 2010 were statistically analyzed. Oike et al. [2014] demonstrated that the lightning whistlers were mainly observed inside the L shell region below 2. They also showed seasonal dependence, diurnal variation of lightning whistlers in the plasmasphere, and comparison study with the ground-based observation revealed consistent results considering the effects of ionosphere. Similar type of statistical study is performed by Suarjaya et al. [2016] using narrow-band waveform receiver named Poynting Flux Analyzer (PFX). Using the PFX, Omega signals transmitted from the ground stations were continuously observed along the trajectories, and the detected signals are valuable for studying the propagation characteristics of VLF waves in the ionosphere and plasmasphere.

Agapitov et al. [2014] evaluated amplitude distributions of hiss, lightning-generated, and other whistler mode waves from terrestrial VLF transmitters obtained from Akebono and fitted as functions of L and latitude for two geomagnetic activity ranges (Kp<3 and Kp>3). Based on this statistics, simplified models of each wave type are presented, and quasi-linear pitch angle and energy diffusion rates of electrons by the full wave model are calculated.

## <GEOTAIL>

GEOTAIL spacecraft has been operated since 1992. The Plasma Wave Instrument (PWI) is continuously collecting the high-resolution waveform data as well as the spectrum data. The color plots of the spectrum data have been opened in the PWI web site http://www.rish.kyoto-u.ac.jp/gtlpwi, and http://www.stp.isas.jaxa.jp/geotail.

Furthermore, one can easily also make the color spectrum plots in flexible time scales in the NICT web page http://geotail.nict.go.jp/.

Li et al. [2014] reported a sub-Alfvenic jet in the tailward outflow region near the separatrix of the magnetic reconnection observed by GEOTAIL. Several dozens of electrostatic solitary waves/pulses (ESWs) were observed, respectively, on the current sheet-side and the lobe-side of the separatrix. The ESWs on the current sheet-side are of type-B with direction outward (toward to the tailward) while on the lobe-side they are of type-A directed to X-line. Comparing these ESWs, they suggested that energies flowing outward from the reconnection X-line are much larger than those flowing inward. The observations show, that electron beams associated with ESWs are much stronger on the current sheet-side than on the lobe-side of the separatrix. Furthermore, the direction of the electron beam on the lobe-side of the separatrix is mainly antiparallel to the ambient magnetic field and it is mainly parallel on the current sheet-side. These results are consistent with the propagation and generation mechanisms of ESWs.

Chorus elements are generated near the magnetic equator (or the high-latitude minimum-B pockets in the outer magnetosphere) as discrete emissions covering a frequency range of 0.1-0.65 $f_{ce0}$, where $f_{ce0}$ is the cyclotron frequency in the generation region, with wave vectors parallel to the ambient magnetic field. Habagishi et al. [2014] made a statistical analysis of upper band and lower band chorus emissions observed by the GEOTAIL spacecraft. They found that the lower cutoff of the upper band emissions coincides with 0.5 $f_{ce}$, while the upper cutoff of the lower band emissions represents 0.5$f_{ce0}$. When 0.5$f_{ce}$ exceeds 0.65 $f_{ce0}$, the chorus emission is observed as a lower band-only emission. As the emissions propagate away from the generation region, it is possible that they undergo the nonlinear damping at half the local cyclotron frequency 0.5$f_{ce}$ because of the quasi-parallel propagation. The nonlinear damping can separate the emissions into the upper band and lower band chorus emissions. Since the local gyrofrequency gradually increases away from the generation region, the upper cutoff of a lower band element should represent half the gyrofrequency at the generation region, whereas the lower cutoff of an upper band element should follow half the local gyrofrequency. Yagitani et al. [2014] confirmed that the frequency sweep rates and amplitudes of the observed chorus wave packets are consistent with those predicted by the nonlinear growth theory of chorus emissions, except for the frequency gap.

The wave modes in the ion-electron hybrid scales, such as the lower hybrid drift wave, has been the center of attention because they enable coupling between electron and ion dynamics and thus can be the agent for the anomalous resistivity. Shinohara et al. [2016] reported the results of a statistical survey on the wave activity in the lower hybrid frequency range observed by GEOTAIL. They stressed the importance of the dawn-dusk asymmetry in the spatial distribution of the electric wave energy densities that coincides with the spatial structure of the reconnection region.

## <Observation by the other STP satellites>

Using the plasma wave and electron data obtained from THEMIS, Kurita et al. [2014] showed a signature of electron pitch angle scattering driven by Electrostatic Cyclotron Harmonic (ECH) waves in the velocity distribution function (VDF). The diffusion curve of whistler-mode waves is used as a proxy to identify changes in VDFs due to wave-particle interactions. They confirmed that the shape of the VDF well agrees with the diffusion curve of whistler-mode waves when whistler mode chorus alone is active. On the other hand, they found that the shape of the VDF deviates from the diffusion curves at low pitch angles when ECH waves are active following the inactivation of chorus waves. The result is observational support for electron pitch angle scattering caused by ECH waves and suggests that ECH waves can contribute to generation of diffuse auroras.

Nakamura et al. [2014] reported observations of electromagnetic ion cyclotron (EMIC) triggered emissions observed by THEMIS outside the plasmasphere. They performed a survey of the THEMIS data and found various types of emissions mainly on the dayside at radial distances from 6 to 10 $R_E$. They studied three distinctive events in detail and compared these events with the nonlinear wave growth theory. They found that the observed relationship between the amplitudes and frequencies of the emissions are in good agreement with the theory. Nakamura et al. [2015] investigated subpacket structures found in EMIC rising tone emissions observed by THEMIS and showed that the time evolution of the observed frequency and amplitude can be reproduced consistently by nonlinear growth theory. They also compared the observed time span of each subpacket structure with the theoretical trapping time for second-order cyclotron resonance, and demonstrated that an individual subpacket is generated through a nonlinear wave growth process, which excites an element in accordance with the theoretically predicted optimum amplitude.

Nosé et al. [2014] studied magnetic fluctuations embedded in dipolarizations in the inner magnetosphere (a geocentric distance of ≤6.6 RE) and their associated ion flux changes using the data from AMPTE/CCE. Seven events of depolarization, which are considered to be excited by the drift-driven EMIC instability, were introduced. They perform particle tracing for H+ and O+ ions in the electromagnetic fields modeled by the linear dispersion relation of the drift-driven EMIC instability and suggest that the electromagnetic fluctuations associated with the dipolarizations can accelerate O+ ions locally and nonadiabatically in the inner magnetosphere. As was demonstrated by Nosé et al. [2016], magnetic field dipolarization is commonly observed in the inner magnetosphere at L=4.5-6.6. It is accompanied by strong magnetic fluctuations that have a dominant frequency close to the O+ gyrofrequency. This selective acceleration of O+ ions may play a role in enhancing the O+ energy density in the storm time ring current.

Nosé et al. [2015] studied the formation process of an oxygen torus during the 12-15 November 2012 magnetic storm, using the magnetic field and plasma wave data obtained by Van Allen Probes. They estimate the local plasma mass density ($\rho_L$) and the local electron number density ($n_{eL}$) from the resonant frequencies of standing Alfven waves and the upper hybrid resonance band. They concluded that the oxygen torus identified in their study favors the formation scenario of supplying $O^+$ in the inner magnetosphere during the initial phase and subsequent drift during the recovery phase.

Using in-situ observations from the Republic of China Satellite-1 spacecraft, Takahashi et al. [2015] investigated the time response and local time dependence of the ionospheric electric field at mid-low latitudes associated with geomagnetic sudden commencements (SCs) from 1999 to 2004. The analysis supports the global instant transmission of electric field from the polar region. In contrast, the peak time detected in the ionospheric electric field is earlier than that of the equatorial geomagnetic field (~20 s before in the PI phase). They also showed that the electric potential distribution is asymmetric with respect to the noon-midnight meridian, explained by the divergence of the Hall current under non-uniform ionospheric conductivity.

Obara et al. [2016] examined a large increase of relativistic electrons in the outer radiation belt and its penetration into the inner radiation belt over slot region using the MDS-1 satellite observations. Result of analyses demonstrates that a large increase took place in the spring and autumn seasons, and they have newly confirmed that the penetration of outer belt electrons to the inner radiation zone took place during the big magnetic storms by examining a pitch angle distribution of the penetrating electrons. They suggested that strong wave-particle interaction should take important roles in both processes.

Parrot et al. [2015] surveyed both expected and unusual events recorded by DEMETER when it was in operation. They showed some events are related to man-made radio waves emitted by VLF ground-based transmitters or power line harmonic radiation. Natural waves such as atypical quasi-periodic emissions or uncommon whistlers were also introduced. In addition to these works, recent wave observation revealed a variety of plasma wave such as compression-induced EMIC waves [Engerbretson et al., 2015], rising-tone magnetosonic waves (MSW) [Fu et al., 2014], and fine structure of plasmaspheric hiss [Summers et al., 2014] in the Earth's magnetosphere.

Plasma waves generated around the plasma wake of a supersonically moving rocket are studied by Endo et al. [2015] using data from an impedance probe and a wave receiver installed on the sounding rocket S-520-26. During the flight of the S-520-26, three types of plasma waves were observed: short-wavelength electrostatic waves such as electrostatic electron cyclotron harmonic waves, upper hybrid resonance mode waves, and whistler mode waves, assuming that the observed waves are produced in the near wake of the rocket. The wave generation mechanisms are discussed by calculating the linear growth rates of electrostatic waves.

## H1.2 Lunar and Planetary Plasma Waves

### <Lunar Mission>

KAGUYA was a Japanese lunar mission to explore the surface distribution of elements and minerals, surface and subsurface structures of the moon, magnetic field and plasma environment around the moon. The Lunar Radar Sounder (LRS) is one of the scientific instruments on board the KAGUYA main orbiter. The LRS consists of two orthogonal 30 m tip-to-tip antennas and three subsystems: the sounder observation (SDR), the natural plasma wave observation (NPW), and the waveform capture (WFC). A main objective of the SDR is to investigate the surface and subsurface structures of the moon using an HF radar technique, and the NPW and the WFC are passive receivers covering the frequency ranges from 20 kHz to 30 MHz, and from 100Hz to 1MHz, respectively.

Bando et al. [2015] investigated subsurface stratifications below Reiner Gamma, albedo feature in Oceanus Procellarum with a high crustal magnetic field, using the LRS/SDR. Taking into account the LRS-determined dielectric constants, the influence of surface clutter, and the energy loss of the LRS radar pulses in the high frequency band (5 MHz), no evidence was found of subsurface boundaries down to a depth of 1000-m at Reiner Gamma. Given the LRS range resolution of 75-m, the source of the magnetic anomaly is considered to be either strongly magnetized thin breccia layers at depths shallower than 75-m, or less magnetized thick layers at depths deeper than 1000-m.

Goto et al. [2016] proposed a calibration method for wave polarization data obtained by LRS/WFC on board KAGUYA. Thanks to the precise calibration, the polarization data were calibrated with a sufficient accuracy. Hashimoto et al. [2015] analyzed polarization characteristics of auroral kilometric radiation (AKR) observed by LRS/WFC. They utilized the lunar occultation of a lunar satellite to determine the source hemisphere of AKR, and the results are examined by ray tracing from the Earth to the Moon. This ray tracing is also applied to "banded AKR" that is observed far from the Earth and in which emissions around 200 kHz are missing.

Narrowband whistler mode waves with frequencies near 1 Hz have been observed near the Moon. Tsugawa et al [2014] revealed that the narrowband spectra, the frequency concentration near 1 Hz, and the relations between the wave vector, magnetic field vector, and sunward directions can be explained by a condition in which the group velocity vector is almost canceled by the solar wind velocity vector in the spacecraft frame. Hereafter, they referred to this condition as the group-standing condition. The spectral density is modified and has a peak at the frequency satisfying the group-standing condition because of the difference of the frequency width between the solar wind plasma frame and the spacecraft frame. In addition, if the waves were decelerated to be group-standing, the conservation of the energy flux results in the intensification of the wave amplitude at that frequency. They also derived the analytical expression of the amount of the modifications, which depend on the group velocity. These effects can explain the narrowband spectra near 1 Hz and support the relations between the wave vector, magnetic field vector, and sunward directions. The estimated frequency, which satisfies the group-standing condition, is in good agreement with the observed frequency within error bars of the estimation. Considering the group-standing condition, they suggested that the narrowband waves observed in the spacecraft frame are originated from oblique whistler mode waves in the frequencies near the lower hybrid frequency, which are possibly generated by reflected ions from the lunar magnetic anomalies.

Tsugawa et al. [2015] investigated harmonic spectral features of electromagnetic waves identified by KAGUYA in the frequencies of several Hz around the Moon. The waves have steepened waveforms peculiarly in the compressional component. The fundamental waves have almost the same properties as narrowband whistler-mode waves with the frequencies near 1 Hz, which have been observed around the Moon. The waves are observed around the terminator region in the solar wind near the lunar magnetic anomalies at the altitudes under 120 km. They suggested that the harmonic spectra are a result of the nonlinear steepening of narrowband whistler-mode waves. Although the narrowband whistler-mode waves have been observed in the upstream region of many planetary bow shocks, such harmonics have rarely been observed there. Since the harmonics are more frequently observed at lower altitudes of the Moon, these waves are possibly caused by lunar intrinsic environments including lunar dusts and local structures of lunar magnetic anomalies.

Nakagawa et al. [2015] studied magnetic fluctuations in the extremely low-frequency (ELF) range from 0.1 to 10 Hz found by the Lunar Magnetometer (LMAG) and plasma experiment (MAP) on board KAGUYA in the deepest wake behind the moon, where the magnetic field is usually quiet. The fluctuations were compressional and non-monochromatic, showing no preferred polarization. They were often accompanied by "type-II entry" solar wind protons that were reflected by the dayside lunar surface or crustal magnetic field, gyrated around the solar wind magnetic field, then entered the deepest wake. The ELF waves persisted for 30 s to several minutes. The duration was often shorter than that of the type-II protons. Most of the waves were detected on the magnetic field lines disconnected from the lunar surface, along which the solar wind electrons were injected into the wake. Since a large cross-field velocity difference is expected between the type-II protons and the solar wind electrons injected along the magnetic field, some cross-field current-driven instability such as the lower hybrid two-stream instability is expected to be responsible for the generation of the waves.

Low frequency waves observed in the vicinity of the moon were reviewed by Nakagawa [2016] in association with modified distribution function of the plasma velocity. Harada and Halekas [2016] summarized an up-to-date catalog of Moon-related particle populations and lunar upstream waves obtained from in situ measurements at low (<~100 km) and high altitudes. It outlines the observed properties of a variety of classes of lunar upstream waves, as well as their generation mechanisms currently proposed, in association with the lunar upstream particle distributions. The lunar upstream region magnetically connected to the Moon and its wake, the fore-moon, represents a remarkably rich zoo of different classes of waves and different types of particles. Although recent observations have substantially enhanced our knowledge by revealing a number of new categories of upstream particles and waves at the Moon, many fundamental questions remain unanswered.

## <Planetary Mission>

Hisaki satellite with the EUV spectrometer (Extreme Ultraviolet Spectroscope for Exospheric Dynamics: EXCEED) is the UV/EUV space telescope dedicated to planetary sciences. Hisaki has provided continuous observations of Jovian system in UV aurora total flux and EUV Io torus plasma distributions and plasma diagnostics, which connected the solar wind information and ground-based radio (Decameter [aurora] - VHF [radiation belt]) and IR (aurora and airglows) observations. Tsuchiya et al. [2015] analyzed the data from the EUV spectrometer continuously observed the Io plasma torus (IPT) brightness. Its variation is caused by the increase in the hot electron population in the region downstream of Io. The longitude dependence suggests that the electron heating process is related to the plasma density around Io. The interaction between Io and the IPT continuously produces a large amount of energy around Io, and 140 GW of that energy is immediately converted to hot electron production in the IPT.

Kita et al. [2015] reported the first comprehensive observations of Jovian synchrotron radiation (JSR) and H3+ emission from the Jovian thermosphere to investigate the generation process of short-term (days to weeks) variations in the Jovian radiation belt. The observations were made by the Giant Metrewave Radio Telescope and NASA Infrared Telescope Facility during November 2011. Variations of the total JSR flux density and thermospheric temperature seem consistent with the scenario, and the brightness distribution of JSR can be explained by the increase in radial diffusion accompanied by internal loss processes.

Many Japanese scientists are involved in planetary mission jointly planned by JAXA and ESA [Kasaba et al., 2014; 2016]. BepiColombo is a Mercury exploration project. It consists of two orbiters; the Mercury Planetary Orbiter (MPO) and the Mercury Magnetosphere Orbiter (MMO). JAXA is responsible for development of the MMO. MMO is at ESA/ESTEC (European Space Research and Technology Centre, Netherlands) from April 2015. For the plasma wave, Plasma Wave Investigation is aboard this spacecraft. JUICE (JUpiter ICy moons Explorer) is the L-class mission of ESA, planned for launch in 2022 and arrival at Jupiter in 2030s. It will spend at least three years making detailed observations of the Jovian system including Ganymede, Callisto and Europa, and finally be on the orbit around Ganymede. For the plasma wave, Radio and Plasma Wave Investigation is aboard this spacecraft and covers the information of the exospheres, surfaces, and conducting subsurface oceans of icy satellites and their interactions with surrounding Jovian magnetosphere. From Japan, High Frequency part (Preamp and Receiver) will be supplied, and provide the highly resolved information of Jovian radiation emitted from Jupiter and Ganymede by the first 3-axis E-field measurement. For the access to the conductive subsurface ocean, RPWI will first observe cold plasma and electric fields, in order to separate the global conductivity and current from the ionospheres. As a byproduct, reflected Jovian radio emission can be expected from the boundary of crust (ice) and subsurface ocean (conductive water).

## H1.3 Ground Observation and Experiment of Plasma Waves

Katoh et al. [2014] investigated the type IV burst event observed by AMATERAS on 2011 June 7, and revealed that the main component of the burst was emitted from the plasmoid eruption identified in the EUV images of the Solar Dynamics Observatory (SDO)/AIA. They showed that a slowly drifting narrowband structure (SDNS) appeared in the burst's spectra. Using statistical analysis, they revealed that the SDNS appeared for a duration of tens to hundreds of milliseconds and had a typical bandwidth of 3MHz. To explain the mechanism generating the SDNS, they proposed wave-wave coupling between Langmuir waves and whistler-mode chorus emissions generated in a post-flare loop, which were inferred from the similarities in the plasma environments of a post-flare loop and the equatorial region of Earth's inner magnetosphere.

Kaneda et al. [2015] investigated the polarization characteristics of a zebra pattern (ZP) in a type-IV solar radio burst observed with AMATERAS on 2011 June 21 for the purpose of evaluating the generation processes of ZPs. The degree of circular polarization was 50%-70% right-handed and it varied little as a function of frequency. Cross-correlation analysis determined that the left-handed circularly polarized component was delayed by 50-70 ms relative to the right-handed component over the entire frequency range of the ZP and this delay increased with the frequency. Our results suggest that the ZP emission was originally generated in a completely polarized state in the O-mode and was partly converted into the X-mode near the source.

Morioka et al. [2015] studied Solar micro-type III burst storms and dipolar magnetic field in the outer corona. In solar micro-type III radio bursts, their frequency of occurrence with respect to radiation power is quite different from that of ordinary type III bursts. Micro-type III bursts occur near the edge of coronal streamers. Electron beams are trapped along closed dipolar field lines in the outer coronal region, which arise from the interface region between the active region and the coronal hole. A 22-year statistical study reveals that the apex altitude of the magnetic loop ranges from 15 to 50 R_S. The apex altitude has a sharp upper limit around 50 R_S suggesting that an unknown but universal condition regulates the upper boundary of the streamer dipolar field.

Shiokawa et al. [2014] reported observations of ELF/VLF chorus waves taken by High-resolution Aurora Imaging Network (VLF-CHAIN) at subauroral latitudes at Athabasca (L=4.3), Canada. ELF/VLF waves were measured continuously to monitor daily variations in VLF/ELF emissions. They found quasi-periodic (QP) emissions whose repetition period changes rapidly within a period of 1 h without corresponding magnetic pulsations. Falling-tone ELF/VLF emissions were also observed with their rate of frequency change varying from 0.7 to 0.05 kHz/s over 10 min. Martinez-Calderon [2015] calculated spectral and polarization parameters of VLF/ELF waves with high temporal resolution using the data measured by the VLF-CHAIN. They suggest that the frequency-dependent events, which usually last several tens of minutes, might be the consequence of the broadening of the ray path that the waves follow from their generation region to the ground. Ozaki et al. [2015b] observed a direct link between discrete chorus elements and pulsating aurora (PA). These observations show a close connection between chorus emissions and PA on timescales from milliseconds for generation of discrete chorus elements on the microphysics of wave-particle interaction to minutes for the variations of the geomagnetic field inhomogeneity related with the substorm activity.

Nomura et al. [2016] studied rising tone emissions with a dispersion of 1 Hz per tens of seconds in a Pc1 on the ground. They demonstrated that pulsations of the proton aurora have one-to-one correspondences with Pc1 rising tones, and suggested that Pc1 rising tones and associated pulsating proton auroras are due to EMIC-triggered emissions. To understand the role of electromagnetic ion cyclotron (EMIC) waves in determining the temporal features of pulsating proton aurora (PPA) via wave-particle interactions at subauroral latitudes, Ozaki et al. [2016b] analyzed Pc1 pulsations that consisted of successive rising-tone elements with a spacing for each element of 100 s and subpacket structures. In accordance with the temporal features of the Pc1 pulsations, the auroral intensity showed a similar repetition period of 100 s and an unpredicted fast modulation of a few tens of seconds. These results indicate that PPA is generated by pitch angle scattering, nonlinearly interacting with Pc1/EMIC waves at the magnetic equator.

Pulsating auroras show quasi-periodic intensity modulations caused by the precipitation of energetic electrons of the order of tens of keV. It is expected theoretically that not only these electrons but also sub-relativistic/relativistic electrons precipitate simultaneously into the ionosphere owing to whistler-mode wave–particle interactions. Miyoshi et al. [2015] analyzed the data observed with the European Incoherent Scatter (EISCAT) Tromsø VHF radar and found electron density enhancements at altitudes >68 km in association with the pulsating aurora, suggesting precipitation of electrons with a broadband energy range from ~10 keV up to at least 200 keV. During this period, the footprint of the Van Allen Probe-A satellite was very close to Tromsø and the satellite observed rising tone emissions of the lower-band chorus (LBC) waves near the equatorial plane. Considering the observed LBC waves and electrons, Miyoshi et al. [2015] conducted a computer simulation of the wave-particle interactions, and showed simultaneous precipitation of electrons at both tens of keV and a few hundred keV. This result revealed that electrons with a wide energy range simultaneously precipitate into the ionosphere in association with the pulsating aurora, providing the evidence that pulsating auroras are caused by whistler chorus waves.

Kurita et al. [2015] reported a case in which relativistic electron precipitations are associated with diffuse aurora based on a conjugate observation between the SAMPEX spacecraft and the all-sky TV camera at Syowa Station. The SAMPEX observation shows that the precipitations of > 1MeV electrons are well accompanied with those of > 150 and > 400keV electrons. This indicates that electrons in the energy range from several keV to > 1MeV precipitate into the atmosphere simultaneously. This result supports the idea that whistler mode waves contribute to both generation of diffuse auroras and relativistic electron precipitations.

Morioka et al. [2014] studied the substorm onset process on the basis of the vertical evolution of auroral acceleration regions derived from auroral kilometric radiation (AKR) spectra and Pi pulsations on the ground. The field-aligned auroral acceleration at substorm onset demonstrated two distinct phases. Low-altitude acceleration (h~3000–5000 km), which accompanied auroral initial brightening, prebreakup Pi2, and direct current of ultralow frequency (DC-ULF) pulsation were first activated and played an important role (precondition) in the subsequent substorm expansion phase onset. Prebreakup Pi2 is suggestive of the ballooning mode wave generation, and negative decrease in DC-ULF suggests increasing field-aligned current (FAC). They called this stage the substorm initial phase. A few minutes after this initial phase onset, high-altitude acceleration, which accompanied auroral breakup and poleward expansion with breakup Pi1 and Pi2 pulsations, suddenly broke out in an altitude range from 8000 to 16,000 km. Thus, substorm expansion onset originated in the magnetosphere-ionosphere (M-I) coupling region, i.e., substorm ignition in the M-I coupling region. Statistical investigations revealed that about 65% of earthward flow bursts observed in the plasma sheet were accompanied by enhanced low-altitude AKR, suggesting that flow braking of bursts causes FAC and resulting low-altitude field-aligned acceleration in the M-I coupling region. On the basis of these observations, they propose a substorm onset scenario in which FAC that originated from the braking of plasma flow bursts first enhances low-altitude acceleration (substorm initial phase onset) and then the increasing FAC induces current-driven instability in the M-I coupling region, which leads to high-altitude acceleration and resulting substorm expansion phase onset.

Teramoto et al. [2014] investigated Pi2 pulsations in the nightside ionosphere observed with high-temporal (8 s) resolution by beam 4 of the Super Dual Auroral Radar Network (SuperDARN) Hokkaido radar. From the radar observations and the IGRF model, the amplitude of the eastward (EEW) component of the electric field of the Pi2 pulsations in the ionosphere was estimated ~8.0 mV/m in the F region and ~2.0 mV/m in the E region. Corresponding Pi2 pulsations appeared dominantly in the horizontal northward magnetic field component (H) at nearby ground stations, Moshiri (MSR), St. Paratunka (PTK), and Stecolny (STC). At the dominant frequency of 8.8mHz, the coherences between H and EEW were high (>0.9), the cross phases of EEW relative to H were −56° and −45°, and the amplitude ratios were 2.7 × 105 m/s and 8.4 × 105 m/s, in the E and F regions, respectively. Based on a comparison of these results with theoretical predictions, they suggested that the concept of a pure cavity mode is not sufficient to explain the combined observations for midlatitude Pi2 waves and that the contribution of an Alfvén waves must be taken in account. Teramoto et al. [2016] studied a harmonic Pi2 wave simultaneously observed by three mid-latitude Asian-Oceanian SuperDARN radars, three THEMIS satellites, and ground-based magnetometers at low and high latitudes. The Poynting flux derived from the electric and magnetic fields indicated that these pulsations were waves propagating earthward and duskward. They suggest that compressional waves propagate duskward away from the midnight sector, where the harmonic cavity mode is generated.

Imajo et al. [2016] statistically analyzed the longitudinal phase and amplitude structures of Pi2 pulsations at middle- to low-latitude stations around both the dawn and dusk terminators in order to clarify the effect of the dawn and dusk terminators on Pi2 pulsations. Some features of the D component Pi2s depended on the location of the terminator rather than the local time. Nosé [2016] studied the long-term variations of substorm occurrences in 1992–2015 that are evaluated with the number of Pi2 pulsations detected at the Kakioka observatory. The results suggest no clear correlation between the substorm occurrence and the Mg II index.

Quarter-wave modes are standing shear Alfvén waves supported along geomagnetic field lines in space. They are predicted to be generated when the ionosphere has very different conductance between the north compared with the south ionosphere. It was suggested that the resonant frequency is sometimes very low around the dawn terminator due to quarter-wave modes. Obana et al. [2015] examined the resonance structure that provides further evidence of the presence of quarter-wave modes using the data from three magnetometers in New Zealand. These observations are strong evidence of the presence of quarter-wave modes and mode conversion from quarter- to half-wave resonances. These experimental results were compared with the ULF wave fields obtained from a 2.5-dimensional simulation model.

Sato et al. [2015] reported polarization measurement of auroral roar emissions near 4 $f_{ce}$ by a ground-based passive receiver in Iceland. In 9 of 11 cases, 4 $f_{ce}$ roar was left-handed elliptically polarized waves. The O-mode 4 $f_{ce}$ roar was observed under both sunlit and dark ionospheric conditions during geomagnetic storms. For O-mode 4 $f_{ce}$ roar generation during darkness, the condition $f_{UH} = 4\ f_{ce}$ might be satisfied by a high-density F region ionosphere due to auroral precipitation or tongue of ionization. In two cases, right-handed elliptically polarized 4 $f_{ce}$ roar was observed during darkness hours and the main phase of a geomagnetic storm. This polarization indicates that nonlinear coupling of two upper hybrid waves may also work to generate X-mode 4 $f_{ce}$ roar. Sato et al. [2016] reported simultaneous measurements of medium-high frequency (MF/HF) auroral radio emissions (above 1 MHz) by ground- and satellite-based instruments. Observational data were obtained by the ground-based passive receivers in Iceland and Svalbard, and by the Plasma Waves and Sounder experiment (PWS) mounted on the Akebono satellite. They found that the frequencies of the auroral roar and MF bursts detected at ground level were different from those of the terrestrial hectometric radiation (THR) observed by the Akebono satellite passing over the ground-based stations. This frequency difference confirms that auroral roar and THR are generated at different altitudes across the F peak. Space- and ground-level detections did not always accompany one another, which were explained as spacecraft could detect THR from wider regions while auroral radio emissions generated in the bottomside F region were masked by ionospheric absorption and screening in the D/E regions associated with ionization which resulted from auroral electrons and solar UV radiation.

Tatsuta et al. [2015] studied quantitatively the effect of geomagnetic storms on the sub-ionospheric VLF/LF propagations for different latitudes based on 2-year nighttime data from Japanese VLF/LF observation network. Pal and Hobara [2016] compared the amplitude of VLF signals with the atmospheric parameters (total column Ozone (TCO) density, stratospheric temperatures etc.) for the first time for three different latitudinal regions to investigate the relationship between the lower atmosphere and upper mesosphere-lower ionosphere (UMLI) region. This study indicates the experimental observation of latitudinal dependence of atmospheric influence on the upper mesosphere. Shimizu et al. [2016] analyzed lightning current waveforms measured by a Rogowski coil installed at Mt. Ogkami and ELF waveforms measured at Onagawa observatory. Based on comparison between the ELF and the current waveforms, empirical equations for conversion from the magnetic field intensities into the current intensities and charge amount were obtained. Using ELF waveform at Kuju station in Kyushu and the Japan Lightning Detection Network (JLDN) lightning data, they newly found a clear feature showing that the time variation of charge amounts drastically changed just before the downburst onset in the Kanto Plain.

Tsutsui [2014] detected electromagnetic (EM) waves directly excited by earthquakes in a deep borehole and confirmed them by simultaneous capturing of their waveforms and of seismic waves measured at the same observation site. Furthermore, the excitation mechanism of the EM pulse was confirmed as the piezoelectric effect by a laboratory experiment, in which a seismic P-wave was readily generated by a small stress impact, and the EM wave was simultaneously excited basically by the P-wave. Tsutsui [2014] showed behaviors of seismic waves and of their excited EM waves when small and large earthquakes occurred, and that the EM waves excited by seismic waves have leaked out of the ground surface.

## H1.4 Laboratory Experiment

Two dimensional microstructures of a high beta and low Mach number quasi-perpendicular collisionless shock and the associated particle acceleration process are investigated [Matsukiyo and Matsumoto, 2015]. Shoji et al. [2016] proposed an experimental design for producing a magnetized collisionless shock by using high power laser and reported a preliminary result of the experiment using Gekko XII laser facility at Osaka University. A high power laser experiment of a spherical shock propagating in an external magnetic field was performed [Kuramitsu et al., 2016a] and electron density, electron and ion temperatures, charge state, and drift velocity of the plasma jet were measured by collective Thomson scattering measurement [Ishikawa et al., 2016]. Matsukiyo et al. [2016] investigated collective Thomson scattering of a monochromatic laser light in non-equilibrium plasmas, which may occur in the vicinity of a collisionless shock. Kuramitsu et al. [2016b] reported experimental results on Kelvin-Helmholtz (KH) instability and the associated vortices in laser-produced plasmas.

# H2. Theory and Computer Experiment on Plasma Waves

## H2.1 Theory and Computer Experiment on Whistler-mode Chorus

Study on wave-particle interaction occurring in the magnetosphere are vigorously performed combining with simulations and observations to clarify generation mechanisms of plasma waves such as chorus and EMIC as well as particle scattering and acceleration. Particle precipitation into the atmosphere is believed to be one of the dominant mechanisms for the loss of energetic electrons from the Van Allen radiation belts. Wave-particle interactions involving ULF through to VLF waves are thought to be important drivers of these loss events. There is growing interest in energetic electron precipitation (EEP). Much of the renewed interest comes from NASA's recent Van Allen Probes mission, which has stimulated new experimental and theoretical research and opened up new understanding into the fundamental physical processes of radiation-belt dynamics [Rodger et al., 2014].

Omura [2014] gave a brief account of the nonlinear theory of the generation mechanism of chorus emissions. The nonlinear dynamics of resonant electrons, and the formation of the electromagnetic electron "hole" that results in resonant currents generating rising-tone emissions are introduced. In contrast, falling-tone emissions are generated through the formation of electron "hills." The mechanism of nonlinear wave damping due to quasi-oblique propagation, which results in the formation of a gap at half the electron cyclotron frequency, is also described.

Omura et al. [2015a] showed a nonlinear theory of chorus waves to explain observations of coherent hiss emissions. They derived optimum wave amplitudes for triggering rising and falling tone emissions and demonstrated that upper limit of hiss is determined by optimum and threshold amplitudes for rising tones. Omura et al. [2015b] proposed a formation process of relativistic electron flux through interaction with chorus emissions. They demonstrated that chorus emissions can accelerate electrons from tens of keV to several MeV within a few minutes, and a dumbbell distribution of relativistic electrons is formed by nonlinear trapping (RTA + URA). Finally, a numerical Green's function method for chorus wave-particle interaction is formulated.

Nunn and Omura [2015] investigated nonlinear wave-particle interaction in oblique whistlers in the Earth's magnetosphere. They derived relativistic electron equations of motion for oblique whistlers and the resonant particle distribution function, resonant current, and nonlinear growth rate are computed.

Katoh [2014] studied the propagation of whistler-mode chorus in the magnetosphere by a spatially two-dimensional simulation code in the dipole coordinates. The simulation system was set so as to assume the outside of the plasmapause, corresponding to the radial distance from 3.9 to 4.1 RE in the equatorial plane and the latitudinal range from −15° to +15°. A model chorus element is assumed to propagate northward from the magnetic equator at L=4 with a rising tone from 0.2 to 0.7 $f_{ce0}$. The simulation results showed that resultant wave spectra observed along the field line are different between the density enhancement and density decrease duct cases. This study clarifies that the variation of propagation properties of chorus should be taken into account for the thorough understanding of resonant interactions of chorus with energetic electrons in the inner magnetosphere.

Katoh and Omura [2016] carried out a self-consistent simulation of the generation process of whistler-mode chorus by a spatially one-dimensional electron hybrid code, by assuming the magnetic field inhomogeneity corresponding to L=4 of the dipole field. They demonstrated that spectral fine structures found in simulation results were similar with the observation by the Cluster spacecraft. But the gap at half the gyrofrequency was not found in simulation results. That implies oblique propagation of the waves with respect to magnetic field, which cannot be treated in one-dimensional simulations, are essential for forming the half gyrofrequency gap.

## H2.2 Theory and Computer Experiment on EMIC Wave

Shoji and Omura [2014] performed parametric analyses of electromagnetic ion cyclotron (EMIC) triggered emissions with a gradient of the nonuniform ambient magnetic field using a hybrid simulation. According to nonlinear wave growth theory, as the gradient of the ambient magnetic field becomes larger, the theoretical threshold of the wave amplitude becomes larger, although the optimum wave amplitude for nonlinear wave growth does not change. With a larger magnetic field gradient, they obtained coherent rising-tone spectra because the triggering process of the EMIC triggered emission takes place only under a limited condition on the wave amplitude. On the other hand, with a smaller magnetic field gradient, triggering of the emissions can be caused with various wave amplitudes, and then the subpackets are generated at various locations at the same time. The concurrent triggering of emissions results in incoherent waves, observed as “broadband” EMIC bursts.

Kubota et al. [2015] performed test particle simulations of relativistic electrons interacting with EMIC-triggered emissions in the plasmasphere. They found that electrons are guided to lower pitch angles by nonlinear trapping and precipitation is modulated by the subpacket wave periods. They concluded that electrons at 0.5-6 MeV are precipitated efficiently by EMIC-triggered emissions.

## H2.3 Mode Conversion Theory in Inhomogeneous Plasma

Kalaee and Katoh [2014] investigated the effect of the spatial scale of the density gradient on the mode conversion efficiency in an inhomogeneous plasma where the mode conversion can occur only by the tunneling effect. For a particular angle of incidence wave, it is possible for a slow Z-mode wave incident on an inhomogeneous plasma slab to be converted into an LO mode wave. For another wave normal angle of the incident wave, however, it has been considered impossible, since an evanescence region exists between two mode branches. By considering the steepness of the density gradient, their simulation results show the efficient mode conversion could be expected even in the case that the mismatch of the refractive indexes prevents the close coupling of plasma waves. They also showed the cases the beaming angle does not correspond to Jones' formula. This effect leads to the angles larger and smaller than the angle estimated by the formula. This type of mode conversion process becomes important in a case where the different plasmas form a discontinuity at their contact boundary.

Recent spacecraft's observations of kilometric continuum radiation showed that the observed beaming angle of radiations often deviates from the prediction of the linear mode conversion theory (LMCT). Satellite observations also show some local fluctuation in the density gradient. Kalaee et al. [2014] considered the mode conversion process from UHR- mode (slow Z- mode) to LO-mode (ordinary) waves, focusing on the effect of the angle between the density gradient and the external magnetic field on the efficiency of the LMCT and the resultant beaming angle of converted LO-mode waves. From the results of analyses, for both perpendicular and oblique cases, the highest conversion efficiency is obtained for a certain value of the wave normal angle (critical wave normal angle) of the incident slow Z-mode waves, corresponding to the case when two mode branches are matched. The simulation results show in the perpendicular case that the beaming angle is consistent with the conventional LMCT; but in the oblique case a critical wave normal angle becomes different from the perpendicular case and the beaming angle is different from the LMCT prediction.

Kalaee and Katoh [2016a] studied a condition required for mode conversion of electrostatic waves propagating purely perpendicular to the ambient magnetic field, by numerically solving the full dispersion relation. Numerical calculation revealed that the angle between the boundary surface and the magnetic field vector should be within a specific range in mode conversion processes in inhomogeneous plasma, which imply that the angle between the magnetic field and the density gradient plays an important role in the conversion process. The effect of the angle between the magnetic field and gradient density on beaming angle of mode conversion process was also investigated by Kalaee and Katoh [2016b]. The calculated beaming angle in this study was consistent with continuum radiation events, which are observed by CRESS and IMAGE.

## H2.4 Other Generation Mechanisms of Plasma Waves

Kakad et al. [2014] performed both fluid and particle-in-cell (PIC) simulations of ion acoustic solitary waves (IASWs) and estimated the quantitative differences in their characteristics like speed, amplitude, and width. They found that the number of trapped electrons in the wave potential is higher for the IASW, which are generated by large-amplitude initial density perturbation (IDP). The present fluid and PIC simulation results are in close agreement for small amplitude IDPs, whereas for large IDPs they show discrepancy in the amplitude, width, and speed of the IASW, which is attributed to negligence of kinetic effects in the former approach.

Lee et al. [2014] presented a brief review of wave generation via the cyclotron maser instability by an electron ring distribution, and the associated electron acceleration by the excited Z-mode and whistler-mode waves. The electron ring distribution can excite X-mode waves mainly in the perpendicular direction, Z-mode waves in the perpendicular and parallel directions, and whistler-mode waves in the parallel direction.

# H3. New techniques

## H3.1 New Instruments and Sensors for Plasma Wave Experiments

It is very important to develop new instruments that are highly miniaturized and lightweight for multipoint observations using small satellites in the Earth's magnetosphere as well as planetary missions [Saito et al., 2014].

Koyanagi et al. [2014] examined the strength and long-term durability of a spin-axis extensible rigid antenna element, made of tri-axial woven carbon fiber-reinforced polymer (CFRP), for a spinning spacecraft. Due to a slight deviation between the spin axis and antenna-extended axis with the spin, the antenna is subjected to centrifugal body force; the centrifugal force enhances the antenna deflection. A relationship between centrifugal force and antenna deflection is derived from beam theory. As the apparent material modulus decreases with time, the deflection increases simultaneously. The time dependence of mechanical properties of the tri-axial woven CFRP is hence examined by a creep test. The time-dependent failure criterion of the antenna is then examined using a flexural durability test. Based on the beam theory and experimental results, they examined the long-term reliability of applying the tri-axial woven CFRP to extensible rigid antenna for the spinning spacecraft, especially for SCOPE mission; it was verified that the current design tolerance for the mission assures certain durability for long-term usage.

In order to considerably reduce circuit resources (mass, volume, and power) for the analog front ends of plasma wave measurement systems, Ozaki et al. [2014] designed a current-sensitive preamplifier for magnetic search coils (MSCs) with standard 0.25-μm complementary metal-oxide-semiconductor (CMOS) technology. Since the input noise current determines the output noise levels around the resonant frequency of an MSC, a CMOS preamplifier operating with low noise current is suitable when combined with an MSC instead of using bipolar junction transistors. A prototype of the CMOS preamplifier was fabricated on a 1.9×3.3-mm2-silicon chip. The noise equivalent magnetic induction of the CMOS preamplifier combined with a 100-mm-long MSC is 3.5 pT/Hz1/2 at 10 Hz and 30 fT/Hz1/2 at 2 kHz with a power consumption of 4.6 mW for a 3.3-V supply. Following this technique, Ozaki et al. [2016a] developed a preamplifier for the 3-axis loop antenna of an electromagnetic sensor probe by using application-specific integrated circuit (ASIC) technology with a 0.25-μm complementary metal-oxide-semiconductor process.

On the other hand, Ozaki et al. [2015a] developed an equivalent circuit model for the electric field sensitivity of a magnetic search coil (MSC) in a collisionless isotropic cold plasma. MSCs are sensitive to both magnetic and electric fields, but detecting electric fields is unnecessary for magnetic observations of plasma waves. It is important to evaluate both sensitivities for different geometries and electrostatic shields to avoid electric field pickup. The electric field sensitivity is defined by a relationship between the MSC impedance and the sheath capacitance. To confirm the validity of the circuit model, the sensitivity to an electric field was measured by imposing an external electric field using charged parallel metallic plates in laboratory experiments. The coupling capacitance between the MSC and charged plates is equivalent to the sheath capacitance in a space plasma. The measured results showed good agreement with an approximate expression deduced from the equivalent circuit model. This agreement supports the validity of the proposed equivalent circuit model. An electrostatic shield having slits is often used to reduce eddy current losses in the shield. It has been found, however, that such slits result in a deterioration of the electric field sensitivity by exposing a part of the sensor coil to the plasma sheath. These results will be useful in evaluating the electric field sensitivity of an MSC covered by an electrostatic shield.

Miyake et al. [2015] developed 3D particle-in-cell simulations including long and extremely thin wire booms as well as a spacecraft chassis, and investigated an electrostatic environment. Even subsonic ion flows can produce an appreciable potential difference between the upstream and downstream sides of the spacecraft, and the potential difference would be detected as a spurious field of a few mV/m. The necessary condition for the spurious field is a relatively high (a few tens of V) spacecraft potential, and also the spacecraft potential hump needs to be expanded by thin wire booms biased at the spacecraft potential. The analysis also reveals that the presence of a heavy ion flow and a field-aligned ion upflow can further enhance the spurious field up to 5 mV/m.

## H3.2 Development of Simulation Codes and Data Analysis Systems

Kitahara and Katoh [2016] proposed a new method to detect pitch angle scattering caused by plasma waves and evaluated the feasibility of the proposed method using the simulation data. The proposed method enables us to identify the location where pitch angle scattering occurs. It can be applied to the results of space-based observations by the forthcoming ERG satellite.

Katoh et al. [2016] developed a spatially one-dimensional electron hybrid code domain-decomposed by OhHelp, a library for PIC simulation with achieving both dynamic load balancing and scalability for the study of the generation process of whistler-mode chorus emissions and relativistic electron acceleration in the Earth's inner magnetosphere. They evaluated the efficiency and scalability of the developed code tested on the system A (Cray XE6) of Academic Center for Computing and Media Studies, Kyoto University.

Sugiyama et al. [2015] studied EMIC wave instabilities in a kappa-Maxwellian and showed characteristics of higher harmonics of EMIC waves. Technical description of KUPDAP dispersion solver is also given.

Wave distribution function (WDF) method is one of most sophisticated direction finding techniques based on the idea that observed signals consist of a number of elementary plane waves that define wave energy density distribution. However, the resulting equations constitute an ill-posed problem in which a solution is not determined uniquely; hence, an adequate model must be assumed for a solution. Ota et al. [2015] proposed a new method for direction finding of the plasma waves measured by plasma wave receivers. Their method is based on the assumption that the WDF can be represented by a Markov random field model with inference of model parameters performed using a variational Bayesian learning algorithm. Using computer-generated spectral matrices, they evaluated the performance of the model and compared the results with those obtained from two conventional methods.

A variety of satellite missions, Earth observations and environments, Space physics and Astrophysics and Commercial uses, are carried out every year. Most of the satellites yield a large-scale data, and high-performance data processing technologies are expected. Murata et al. [2013a] developed a cloud system (the NICT Science Cloud) for big data analyses of Earth and Space observations via spacecraft. They proposed a new technique to process large-scale data with paying attention to the fact that high-speed I/O (data file read and write) is important compared with data processing itself. They also adopt a task scheduler, the Pwrake, for easy management of parallel data processing. Many functions are expected to the science cloud; such as data standardization, data collection and crawling, large and distributed data storage system, security and reliability, database and meta-database, data stewardship, long-term data preservation, data rescue and preservation, data mining, parallel processing and so on., data publication and provision , semantic web, 3D and 4D visualization, out-reach and in-reach, and capacity buildings [Murata et al. 2013c; Watanabe et al., 2014a; Murata et al., 2014a; 2014b]. Due to rapid increase of network bandwidth in recent years, Watanabe et al. [2016] discussed a distributed file system for high performance computing to store large-scale data such as plasma simulations or observations. They developed a tool working in long fat networks (LFNs) between Japan and USA with its latency (RTT: round trip time) of 152ms and throughput of 7Gbps in reading and 5Gbps in writing.

Many applications were performed on the NICT Science Cloud for the evaluation of the system and for practical use. It is pointed out that research environment for circulation and utilization of observation data in many research fields, including the Solar-Terrestrial Physics (STP), is not sufficient because the data formats of observation data are not common. To overcome this problem, a database system designed for Linked Open Data and Semantic Web was proposed by Murata et al. [2013b].

Using a set of long-time scientific satellite observation data (GEOTAIL satellite), Murata et al. [2014c] examined the performance of the system on the NICT Science Cloud. They successfully archived high-speed data processing more than 100 times faster than those on traditional data processing environments. The 3D phased array radar equipped in the Osaka University of Japan rotates in 30 seconds to capture a 3D structure of (strong) rain within 60km in radius and 15km in altitude. Watanabe et al. [2014b] succeeded in developing a real-time 3D visualization system which enables to draw the 3D animation of rain structure (51MB/step) at a remote client computer of Tokyo within 70 seconds after every rotation. In order to realize the concept of the World Data System (WDS), Murata et al. [2014e] proposed a Web application for interdisciplinary researches working on the NICT Science Cloud. Based on our design of the Web with help of HTML5 and Ajax technologies, we implemented a Web using a couple of mission datasets. Data plots are previewed on the Web application with higher usability than traditional data plot tools. Kubota et al. [2014] developed a system of Magnetic Field Tracing in Global MHD simulations in order to understand magnetosphere convection. To trace magnetic flux tube with high precision, they introduced a parallel distribution visualization technique for magnetic field tracing by using NICT science cloud. Yagi et al. [2015] analyzed a set of waveform data measured by the WFC-L receiver on board KAGUYA importing their original program, without rewriting, on the NICT science cloud. They demonstrated that easy task scheduling and parallel processing is effective and practical for big data analysis even in case that the data set is heterogeneous. The results of research works using the cloud system are also summarized in Murata et al. [2014d] focusing on how we effectively take advantage of a cloud system on research works in various fields.

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