Proposal of a space science mission concept
宇宙科学ミッションコンセプト提案書

In reply to JFY2022 Announcement of Opportunity for competitive M-class missions
提案機会：公募型小型 2022 年度公募

submitted on August 29, 2022

Summary[1]

Mission name		
	(English)	FACTORS (Frontiers of Formation, Acceleration, Coupling, and Transport Mechanisms Observed by the Outer Space Research System)
	(Japanese)	
Proposing working group (WG)		
	Under the advisory committee of	Science
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Concept Study Report
概念検討書

FACTORS　WG

Date August 29, 2022　version 1.1

1 Summary of the proposal

1.1 Science goals and objectives

To reveal the energy coupling mechanisms and mass transport between the space and planetary atmosphere through various physical and chemical coupling processes across various temporal-spatial scales which play unknown but significant roles on the evolution of planetary atmosphere and habitability, the FACTORS mission investigates the key region at 350–3500 km altitude as a representative coupling region between the space and the Earth in an ideal planet with all thick atmosphere, liquid water oceans, and large magnetosphere caused by intrinsic magnetic field. FACTORS will cover both ways of the coupling processes, inflow from the space and outflow from the Earth because of the interactions. The goals and objectives of the mission are 1) understanding inflow processes that produce aurorae as a manifestation of energy input with various scales and energy coupling between space and atmosphere by carrying out the simultaneous observations of electromagnetic field, plasma particles, and auroral imaging. 2) understanding outflow processes by identifying which types of plasma waves play important roles in accelerating ions to exceed escape velocities in the upper atmosphere. The FACTORS mission is composed of multiple satellites with small satellite separation distances (down to <10 km), with each satellite equipped with comprehensive instruments for plasma and fields. The satellites also carry auroral imagers to observe auroral emissions at footprints along the geomagnetic field line to specify the spatial scale of energy inflow by comparing plasma and field. In addition, the FACTORS mission determines the relevant wave modes that accelerate ions, by combining the multi- and single-satellite interferometric observations of electromagnetic field with plasma velocity distribution functions for electrons and ions.

1.2 Science investigations, instrumentation

The FACTORS mission will perform the simultaneous observations of plasma and fields, and auroral imaging with high-time and spatial resolutions in the altitude range from 350 km to ~3500–4000 km with the inclination between 70° and 90°, which is the key region for the space plasma acceleration and terrestrial ion outflow. FACTORS mission will realize formation flight observations by two small satellites, FACTORS-A and -B, with the satellite separation distance down to <10 km. FACTORS will derive the frequency and wavelength of plasma waves, and identify which modes of waves contribute to various scales of auroral structure. FACTORS will apply the advanced method of Wave-Particle Interaction Analyzer (WPIA), on which the Japanese group has heritages. FACTORS will also conduct the interferometric observations between two satellites to determine the direction of propagation and wavelength of the waves, and their contribution to electron and ion accelerations. FACTORS will carry the scientific instruments shown in **Table 1.2-1**.

The scientific operations will be optimized in the four observation regions in the polar region, and the survey mode and the burst mode will be selected according to observational objectives. One of the most important scientific operations is to acquire in-situ observation data in the auroral zone while controlling the attitudes of two satellites so that the fields of view of the auroral imagers include the ionospheric footprints of the magnetic field lines through the satellites.

The FACTORS mission may include one optional ~60 kg microsatellite provided by Swedish National Space Agency. The third-point observations are able to resolve the instantaneous 2D structures (horizontal/vertical) and dynamics of auroral physical processes.

Table 1.2-1. Science instruments onboard FACTORS-A/B. O: onboard, ×: NOT onboard.

Instrument	Simple description	FACTORS-A	FACTORS-B
MGF	Fluxgate magnetometer	O	O
EPWI	Electric field and plasma wave investigation	O	O
LP	Langmuir probe	O	O
LIMS	Low-energy ion energy-mass spectrometer	O	O
SIMS	Supra-thermal ion energy-mass spectrometer	O	×
SIMS-G	Supra-thermal ion energy-mass spectrometer for gyration phase capture	O	×
LESA	Low-energy electron spectrum analyzer	O	O
HESA	High-energy electron spectrum analyzer	×	O
VISAI	Visible auroral imager	×	O
FUVI	Far-ultraviolet imager	O	×

1.3 Spacecraft system and mission operation

[Spacecraft system]

Two 180 kg class small FACTORS satellites of the same type developed in Japan will be simultaneously launched by the Epsilon S launch vehicle. In addition, if there is a surplus in weight, we will consider to launch a 60 kg class micro satellite Innosat provided by SNSA/OHB of Sweden as an option. In order to carry out direct observation of physical processes occurring in the space-Earth coupling system, the satellite must be as light as possible in order to reach an orbit inclination of 75 degrees or more and the perigee and apogee altitudes of 350 and 3500 km or more. Two FACTORS satellites and one Innosat are mounted on an Epsilon S rocket in a vertically stacked configuration for launch. The FACTORS satellites are equipped with one liquid propulsion system using N2H4 as propellant, with four 1 N-class thrusters. Up to 20 kg of propellant are utilized for controlling and maintaining formation flight configuration. Uchinoura Space Center, GN stations, and the Antarctic Syowa station are candidate ground stations to receive FACTORS data. S band is used for commanding and receiving house keeping data while X band is used for receiving mission data. Expected data rate is 6.5 Gbytes/day for the X band data and 0.2 Gbytes/day for the S band data. As a special request, electromagnetic compatibility requirements are defined to assure the satellite bus and instrument performance.

[Operation profile]

The FACTORS mission requires to control the separation distances (best: 1 km, worst: 10–50 km) between satellites with several types of the formation flight configuration. The inter-spacecraft distance between the satellites is controllable by both delta-V and attitude control, latter of which adjust the air drag force. Since this type of the attitude control operation is critical in order to maintain/control the satellite formation flight configuration with the separation distance of ~1 km (best), and also crucial to avoid fatal problems such as in-orbit crash between satellites, we classify this type of operation as a time-critical event. In the high latitude auroral zone, the satellite attitude is controlled such that the fields of view of the auroral imager covers the footprint of the magnetic field line, and that the planar fields of views of the electron and ion instruments contain the magnetic field line.

1.4 Key technologies and major risk

Key technologies and major risks are summarized in **Table 1.4-1**.

Table 1.4-1. Key technologies and their involved major risks.

Subsystem / category	Key technologies	Major risks
EPWI	Tri-axial electric field sensor	Excess of the necessary resources
SIMS, SIMS-G	Electrical field-of-view switching	Accrual of technical difficulties
SIMS, SIMS-G	Electrical sensitivity control	Accrual of technical difficulties
SIMS, SIMS-G, LIMS	High-speed preamplifier ASIC	Not enough performance of the developed ASIC
VISAI	Optics and photon imaging detector	Accrual of technical difficulties
FUVI	Optics, solar scattering light shielding, visible light blocking, and photon imaging detector	Accrual of technical difficulties
Bus system	Formation flight	Not enough ability of the orbit correction and the attitude control
Development strategy	Simultaneous development of two satellites	Impact on the mission schedule
Launch system	Insertion of multiple satellites in almost identical orbit	Not suitable configuration in the vertical stacking launch system

1.5 Threshold science mission

The threshold science mission (TSM) allows for a well-designed seven descopes of instruments that achieve significant saving in mass, cost and resources if necessary. The minimum TSM is composed of one full spacecraft and one microsatellite. For this case, measurement uncertainties increase for both wave characteristics and 2D spatial distribution of characteristic energy of precipitating electrons, having partially impact on Goal-1 defined in Section 1.1. Measurement difficulty also increases for detail characteristics of waves to accelerate ions, having partially impacts on Goal-2 defined in Section 1.1. Nevertheless, the TSM is still able to specify the spatial scale of energy input to the atmosphere, acceleration mechanisms, and energy inflow from there. The TSM is also able to specify wave modes to contribute for mass/energy outflow.

1.6 Cost estimation

The total cost of FACTORS is 17.99 billion JPY including the appropriate margin (3.25 billion JPY). The breakdown of the cost is, 3.5 billion JPY for the Epsilon S launch vehicle, 6.98 billion JPY for the development of satellite bus system, 3.76 billion JPY for the development of science instruments, 0.08 billion JPY for the ground system development, 0.35 billion JPY for initial operations and one year of nominal operations, and 0.07 billion JPY for others.

1.7 Project Organization

The instrument/science teams of the FACTORS mission consist of researcher, for example in JAXA, Nagoya Univ., Kyoto Univ., Tohoku Univ., Osaka Univ., Kanazawa Univ., Toyama P. Univ., Univ. Tokyo, NIPR, NICT, and the other institutes/universities in Japan, several Swedish groups with a contact point at IRF, and other countries. It should be noted that a science center would be organized and managed by the project scientist in order to integrate the whole research activities in FACTORS, such as the ground-based observations, the modelling/simulation, and the data analyses, in addition to the satellite observations, based on the heritages/achievements by the ERG science center and the Center for heliospheric science by ISAS/JAXA and Nagoya Univ.

2 Science goals of the mission [1-1-1]

The goal of the mission is to unravel the complicated and dynamical relationship between the space and planetary atmosphere evolving through various coupling processes across scales, and their consequence on the planetary atmospheric environment and its habitability in the universe.

3 Scientific objectives of the mission [1-2-1]

Taking advantage of the Earth's upper atmosphere and exosphere at 350–3500 km altitude as a representative coupling region in a magnetized planet, the FACTORS mission is to elucidate the energy coupling and mass transport processes between the space and Earth's atmosphere. FACTORS will address both ways of the coupling process: 1) interactions between the upper atmosphere and inflow from space and 2) outflow from the Earth as a result of this interaction as shown in **Fig. 3-1**.

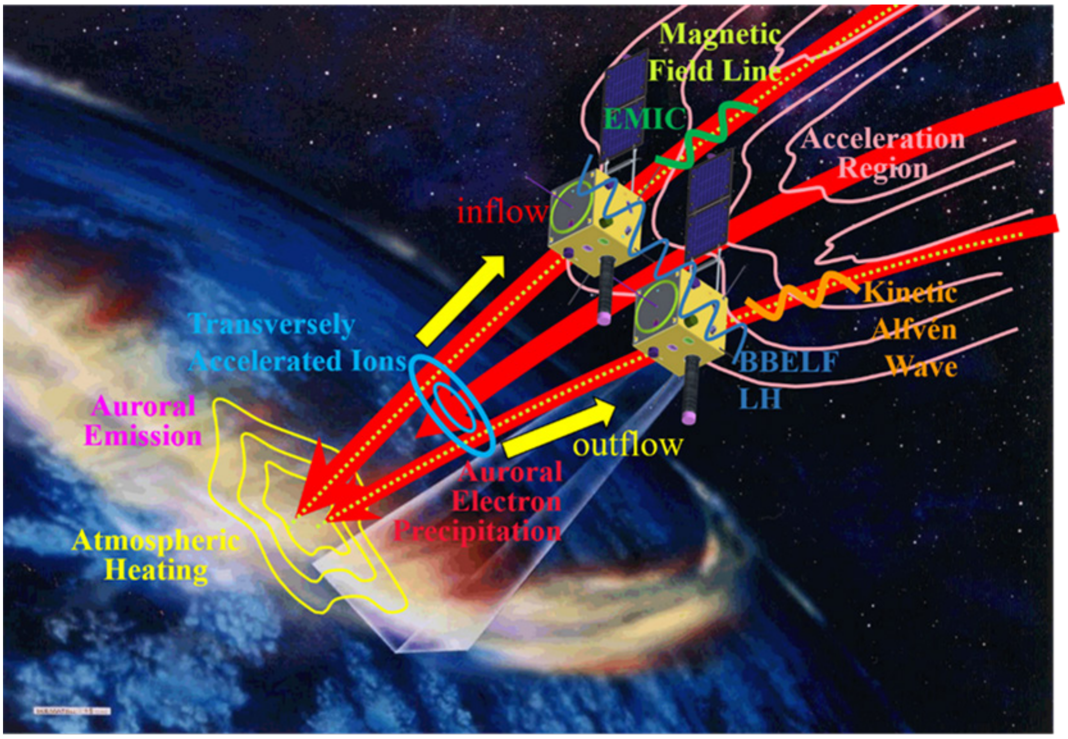

Fig. 3-1. Concept of FACTORS observation that investigate the coupling processes between the space and the Earth.

1) **Objective 1: Energy inflow process**

FACTORS will identify how the space and the terrestrial atmosphere are coupled to produce small-scale phenomena, such as aurora as the manifestation of energy inflow and atmospheric heating, by carrying out the simultaneous observations of electromagnetic field, plasma waves, plasma particles, and auroral emissions. With two closely-flying satellites, FACTORS will discriminate spatial and temporal variations, and thereby for the first time elucidate the multi-scale and inter-regional energy coupling between space and atmosphere.

2) **Objective 2: Mass/energy outflow process**

FACTORS will determine the relevant wave modes that accelerate ions perpendicular to the magnetic field in the Earth's upper atmosphere to cause ion outflows. Combining the interferometric observations of electromagnetic field with species-discriminated observations of ion velocity distribution functions, FACTORS will identify the ion acceleration processes.

4 Rationale for the scientific goals and objectives

In the solar system, the Earth is the only planet that has all of the thick atmosphere, liquid water oceans, and a large magnetosphere generated by interactions between the intrinsic magnetic field and the solar wind. Unlike the gas giants of Jupiter and Saturn, where the planetary rotational force dominates in the magnetosphere, the supersonic plasma flow from the Sun, the solar wind, controls the Earth's magnetosphere dynamics (geospace). Therefore, the Earth's atmosphere and oceanic environments are greatly affected by the radiation, magnetic fields, as well as charged particles emitted from the Sun. The solar radiation and energetic particles that reach the atmosphere ionize the neutral atmosphere and create layers of plasma called the ionosphere, while the solar wind energy is converted to the electromagnetic energy and stored in the magnetosphere. As a result, the electromagnetic energy is transferred along the magnetic field, and drives a variety of phenomena in the upper atmosphere and ionosphere. This inter-regional coupling and the physics behind many of ionospheric phenomena are not only on the Earth, but also common on various planets and satellites in the solar system and many planets in the universe, and often results in a visible phenomenon like the aurora. Even on Mars, which has no intrinsic magnetic field and thin atmosphere, there is aurora-like emission caused by the plasma acceleration and outflows over the crustal magnetic field. Thus, knowledge of the Earth's magnetosphere-ionosphere coupling processes can help us understand the other planets and satellites in the universe.

In the case of Earth, the solar wind energy of both the plasma and the fields enter the ionosphere through both the dayside cusp region, and the nightside magnetosphere. These energies dissipate on their way as well as at the ionospheric destination. As compared to the relatively direct entry through the dayside cusp, the nightside route is complicated and has two major pathways. One of them is the inner magnetosphere (low latitude as mapped to the ionosphere) where high-energy trapped particles form the radiation belts and the ring current during magnetic storms, and a significant part of these particles finally precipitate into the ionosphere. The other entry process takes place via the pathway through the polar region (mapped to the high latitude ionosphere) where the energy flows into the upper atmosphere in the form of plasma waves and charged particle precipitations. All pathways provide sufficient energy to the ionosphere to affect the Earth's upper atmosphere, resulting in the auroral emission, atmospheric heating, and composition change in the thermosphere/the middle atmosphere. Inversely all the pathways are also affected by the ionospheric phenomena, causing inter-regional coupling.

4.1 Scientific background, status of the relevant scientific area, etc.

The satellite observations in the 1980–1990 such as Dynamic Explorer (DE) (launched in 1981) and Akebono (1989) investigated large-scale aspects of the energy inflow into the upper atmosphere and have found that the space and the atmosphere are strongly coupled with each other through electric currents and precipitation of plasma particles. The observations have also revealed the permanent operation of ion outflows and the ion acceleration/heating perpendicular to the magnetic fields in association with various plasma waves near the dayside cusp and in the auroral zone [Yau et al., *Space Sci. Rev.*, 1999].

In the late 1990s and early 2000s, the Fast Auroral SnapshoT (FAST) (1996) and Reimei (2005) satellites conducted high-time resolution (a few tens of millisecond) observations of particles and electromagnetic fields, and clarified that the generation of small scale phenomena by the plasma waves play an essential role on to the coupling between space and the atmosphere. However, the small-scale characteristics of these coupling processes and their relationship with large-scale phenomena are not still understood fully because FAST and Reimei satellites did not perform comprehensive observations of electromagnetic fields, particles, and auroral imaging, all of which are necessary for understanding the small-scale process. Early single-spacecraft interferometric observations made by the FAST satellite and sounding rockets have reported cases in which short wavelength components were included in plasma waves observed in conjunction with accelerated ions. However, the observations have not covfered wide enough range of wavelength, and overall characteristics of plasma waves and their contribution to ion accelerations remain unclear. With comprehensive plasma instruments Cluster and MMS are ideal satellites to study plasma waves and wave-particle coupling, but their perigees are too high to examine the ionosphere and there is no imager.

For deepening our understanding of the physical mechanisms of the space-atmosphere coupling systems, the Earth will contribute to understanding of ion outflows and resultant atmospheric evolution from other planets and even ions outflows from exoplanets, which have been discovered in recent years. For such advance of the knowledge, in-situ measurements by satellites (e.g., Akebono, Geotail, Reimei, and Arase) are inevitable because only in-situ measurements can provide quantitative values. What are needed are detailed values such as plasma velocity distribution function and electromagnetic (wave) field, which are so far impossible to obtain by remote observations without many simplified assumptions and are even not measured by past satellite for necessary accuracy. The FACTORS mission will measure these physical parameters using a state-of-art techniques at two points utilizing a coordinated flight of two spacecraft with inter-spacecraft distance from much less than 10 km to 100 km. This enables us to resolve complex spatial distributions and fast time-varying phenomena and thus explore various phenomena with a wide range of scales from 10 m to 100 km.

4.1.1 Energy Inflow Process

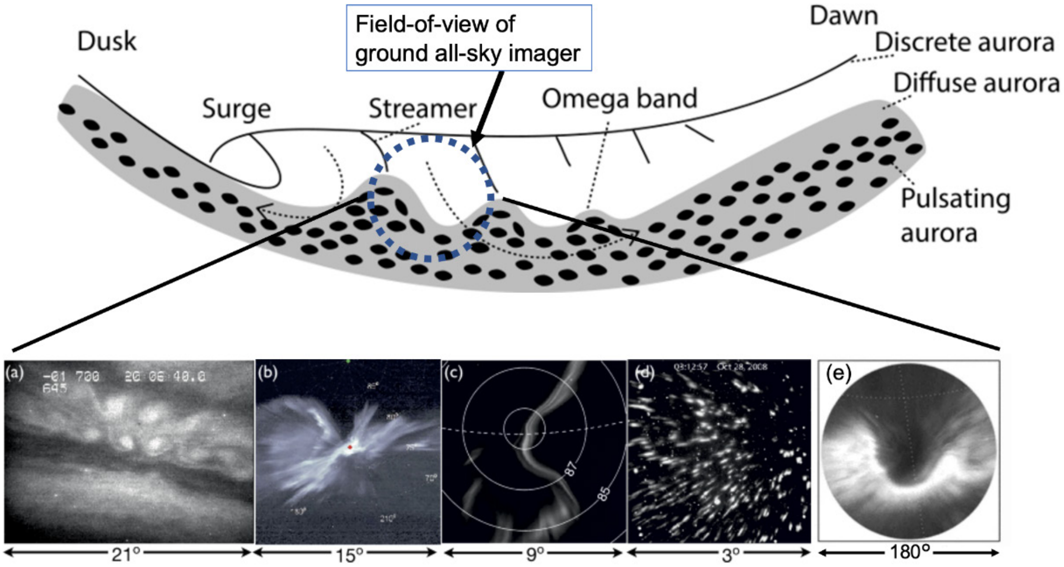

Fig. 4.1.1-1. Small-scale auroral phenomena seen from the ground with various field-of-views. Top: a schematic drawing of large- and medium-scale aurora in a few thousand kilometers range. Bottom: a) aurora curls, b) flaming, c) aurora packets, d) decameter filament e) Omega band (after Kataoka et al., *Space Sci. Rev.*, 2021; Nishimura et al., *Space Sci. Rev.*, 2021; Sato et al., *J. Geophys. Res.*, 2015)

Aurora is atmospheric luminous emission generated by a collision of atmospheric particles when charged particles precipitate from space and the manifestation of energy inflow. Aurora appears in a variety of sizes from hundred meters to thousands of kilometers and in complex structures [Partmies et al., *Ann. Geophys.*, 2010], suggesting that the energy input by the precipitating energetic particles and electromagnetic energy input and/or coupling process are spatially and temporally multi-scale phenomena [Nishimura et al., *Space Sci. Rev.*, 2021]. The multi-scale nature of the energy input is essential for the feedback from the atmosphere to space as well as energy dissipation [Keiling et al., *Science*, 2003; Kataoka et al., *Space Sci. Rev.*, 2021].

Several processes contribute to the field-aligned accelerations of energetic electrons in the auroral region, and the multi-scale characteristics of aurora is a key to understanding the energy input and transfer from space to atmosphere as well as energy dissipation. For example, field-aligned accelerated electrons contribute to discrete arc and Alfvenic aurora and inverted-V and dispersive Alfven waves cause such accelerations. Small-scale structures (curls, flaming, packets and filament) are observed (**Fig. 4.1.1-1**). Pitch angle scattering by plasma waves cause diffuse aurora and pulsating aurora, which are faint emission, but high-energy electron precipitation can also be observed. The large-scale structures of Omega-band that involves both discrete aurora and diffuse aurora are often found on the morning side. Differences in the aurora morphology corresponds to different mechanisms of precipitating electrons.

The horizontal distribution of aurora reflects the energy flux distribution of precipitating charged particles from the space to the atmosphere. Therefore, the auroral two-dimensional morphology and emission spectra provide information about locations and types of energetic electron precipitation from space that are related to the coupling between space and atmosphere.

In 1980–1990s, when the Akebono, Viking (1986) and DE satellites revealed large-scale aspects of the energy flow into the upper atmosphere and suggested strong coupled through the space and atmosphere with electric currents or carrier electrons and ions, the auroral image could gave only large-scale morphology. The resolution of both the imager and plasma measurements improved in 1990s by Freja (1992) and FAST which carried out high-time resolution observations of particle and electromagnetic fields, and confirmed the importance of small-scale structure and its relevance to the wave-particle interactions, i.e., the plasma waves generating the small-scale phenomena, and suggested that they play an essential role on to the connection between space and atmosphere [Chaston et al., *Phys. Rev. Lett.*, 2008]. Their orbits are too high (>1600 km) to examine what is happening in the ionosphere.

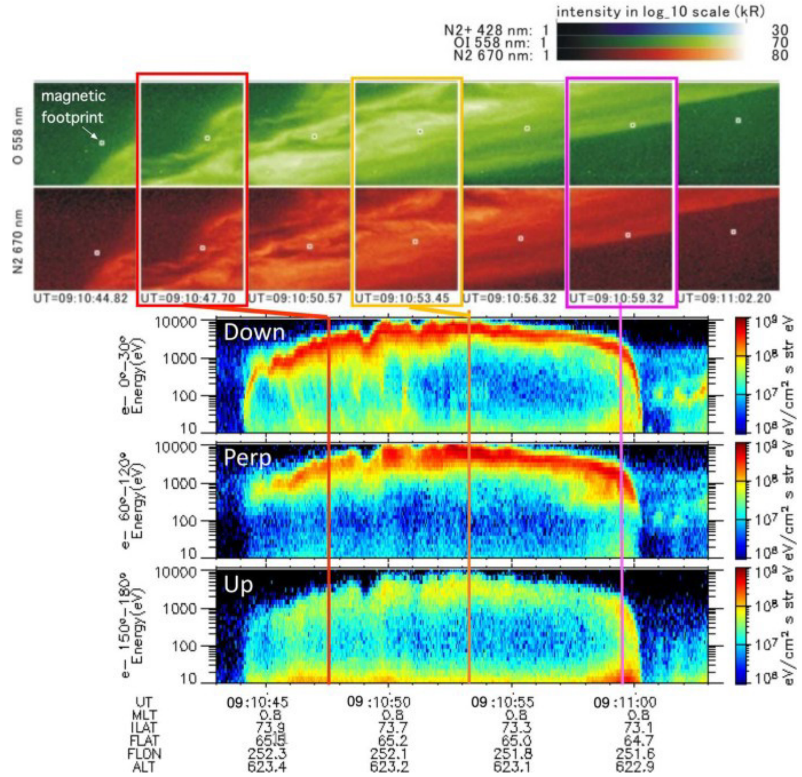

Fig. 4.1.1-2. Reimei observations about Inverted-V and Alfvenic (small-scale) aurora [Kataoka et al., *Space Sci. Rev.*, 2021]. Top: auroral images (558 nm, 670 nm) taken from Reimei. Bottom: energy time diagram of electrons.

Finally, in 2000s, Reimei satellites explored upper ionosphere (altitude of 650 km) with unique set of high-time resolution plasma observation with imager viewing the footprint of the satellite [Asamura et al., *Geophys. Res. Lett.,* 2009] and revealed that small scale aurora is strongly related to the small-scale structure of energization (**Fig. 4.1.1-2**). Reimei carried limited instrumentation and did not observe field and plasma waves. Cluster (2000) also studied auroral acceleration region at mid-altitude [Marklund et al., *J. Geophys. Res.*, 2011] with comprehensive plasma instruments, but their perigees are too high to examine the ionosphere and there is no imager.

Therefore, Fast and Reimei revealed the importance of the small-scale structures and wave-particle interactions as shown in **Fig. 4.1.1-3**. However, characteristics of these small-scale structures and their relationship to large-scale phenomena are still unresolved, because the FAST and Reimei satellites did not perform comprehensive observations of electromagnetic fields, particles, and auroral imaging, which should be necessary for understanding the small-scale process as well as couplings to large-scale phenomena.

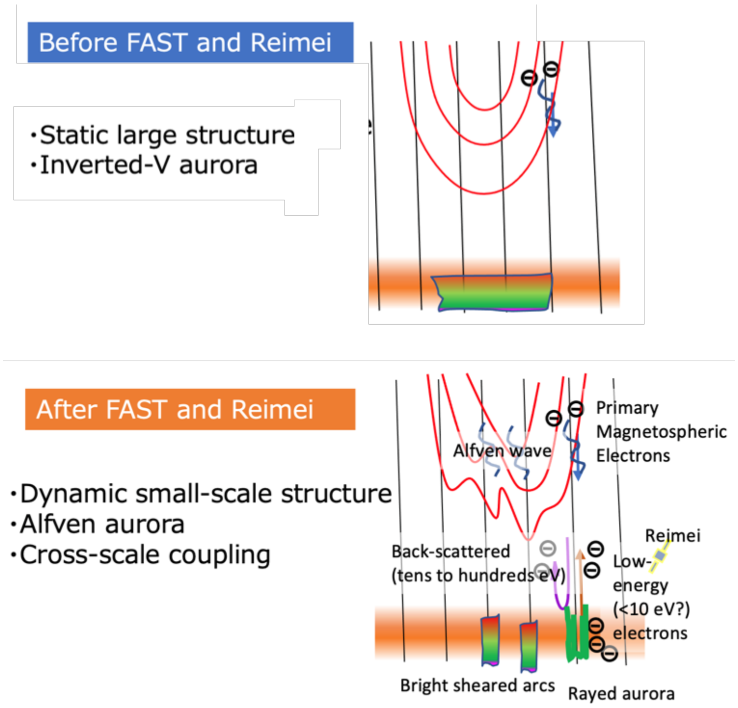

Fig. 4.1.1-3. Schematic picture about understanding of field-aligned acceleration region. (left) Before FAST and Reimei era, static large structure is important for the magnetosphere-ionosphere coupling. (right) FAST and Reimei have provided dynamical picture of small—scale structure caused by Alfven waves.

4.1.2 Mass/energy Outflow Process

From the Earth's upper atmosphere, ions continuously flow upward to the space. These ions reach and populate various regions in the magnetosphere (see **Fig. 4.1.2-1**) [Seki et al., *Science*, 2001; Yamauchi, *Ann. Geophys.*, 2019], and affect plasma phenomena there. For example, observations by Arase and other satellites [e.g., Keika et al., *Geophys Res. Lett.*, 2018] have revealed that the different behavior between O^+ ions, which is of terrestrial ionospheric origin, and H^+ ions, supplied from both the terrestrial ionosphere and the solar wind, plays an important role in the development and recovery of geomagnetic storms. Thus, ion outflows from the ionosphere are crucial to magnetospheric physics, while the physical processes that cause the ion, especially heavy O^+, outflow from the ionosphere are not well understood: the necessary conditions to drive intense ion outflows, how many different steps ions go through to exceed their escape velocity, and their transport paths are still unclear.

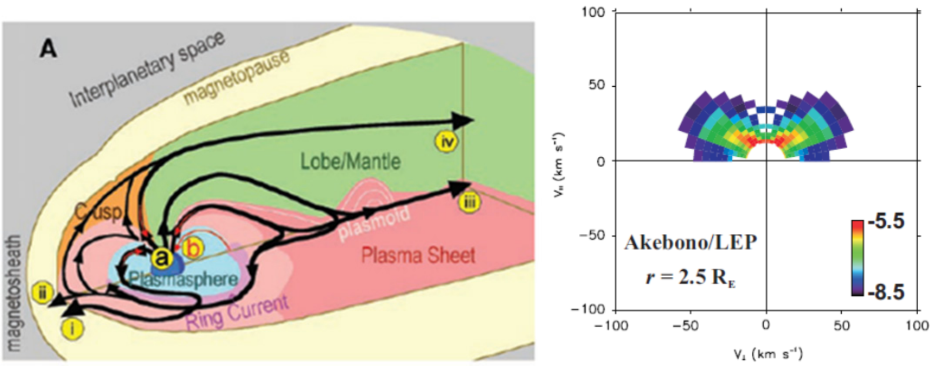

Fig. 4.1.2-1. (left) Overview of the Earth's magnetosphere and various transport paths of outflowing ions from the polar ionosphere [Seki et al., *Science*, 2001]. (Right) Velocity distribution function of ion conics observed by the Akebono satellite (the situation in which the ion velocities are gradually approaching parallel to the magnetic fields due to the effect of magnetic field intensity gradients after being accelerated perpendicular to the magnetic fields) (Color bar: phase space density in /(cm^3(km/s)^3)) [Bouhram et al., *Ann. Geophys*., 2004].

The ion escape is also important even for planetary evolution, at least for magnetized planet. Total amount (flux) of heavy ion loss rate from the Earth to the space strongly depends on the geomagnetic activity [Yamauchi, *Ann. Geophys*., 2019]. Considering the expected escape by high geomagnetic activity (due to high solar activity) in the ancient time (~3 to 4 billion years ago), we expect at that time a 10^{28} /s escape rate. With this escape rate, only 100 million years is enough to change 10% of the equivalent of today's atmospheric oxygen content, and enough to affect the bioactivity.

The energization of ionospheric ions has been detected since late 1970s using in-situ observations of polar-orbiting satellites (including Akebono and Reimei) and sounding rockets, in both forms of field-aligned acceleration and heating in the direction perpendicular to the magnetic fields (see **Fig. 4.1.2-1**), near the dayside cusp as well as in the auroral zone. Observations indicate that ion energization perpendicular to the magnetic field takes place at least at altitudes above several hundred kilometers, and that they play a critical role in achieving acceleration of ions over their escape velocity. However, this energization cannot be explained solely by simple energy/momentum inputs to the ionosphere, such as auroral electrons, precipitating ions, or incoming electromagnetic waves. As described below, the major hypothesis for the ion energization so far is that inflowing energy from space is first converted into plasma waves, and the waves accelerate ions in the direction perpendicular to the magnetic field and finally the ions achieve the escape velocity along the field line because of the mirror motion.

Many processes of the ion energization have been proposed, including acceleration through the wave-particle interaction involving various mode of waves, such as Alfven waves, ElectroMagnetic Ion Cyclotron (EMIC) waves, ElectroStatic Ion Cyclotron Harmonic (ESICH) waves, waves near the Lower Hybrid resonance frequency (LH waves), and acceleration by tilted quasi-static strong electric fields (double layers). However, the plasma waves usually observed with accelerated ions are broadband low-frequency (BBELF) waves, showing a broad frequency spectrum [e,g., Lund et al., *J. Atmos. Solar-Terr. Phys*., 2000; Kasahara et al., *J. Geophys. Res*., 2001], and it is unclear which type of plasma waves forms the apparent BBELF waves. It is thus essential to identify the mode of plasma waves to understand how the ionospheric ions are accelerated and flow out to the magnetosphere.

A single point observation by a single satellite, which moves very fast (>5 km/s in the altitude range of FACTORS due to its orbital motion) cannot recognize whether the observed plasma waves are mainly characterized by temporal variations or spatial variabilities (spatial structure observed as plasma waves or short-wavelength waves observed at frequencies different from that at the plasma rest frame due to large Doppler shift caused by satellite motion). In addition, past satellites did not carry three pairs of identical electric field sensors to measure the complete electric field waveform. Such a 3D waveform observation is particularly important for the identification of electrostatic waves. Despite its importance, the latest satellite with plasma measurements onboard to be inserted into the region of 1500–4000 km altitude was the FAST satellite, which was launched ~25 years ago. FACTORS will provide a great opportunity to yield a significant "update of observations" in this regard for the first time in over three decades (~35 years).

4.2 Goals and objectives: new scientific steps the proposed concept aims to achieve in the science area

The FACTORS mission defines the mission goals as follows to achieve the science objectives defined in Section 3.

(Mission Goal-1: Understanding inflow process)

Understanding inflow processes that produce the small-scale aurora and energy coupling between space and atmosphere by carrying out the simultaneous observations of electromagnetic field, plasma particles, and auroral emissions.

(Mission Goal-2: Understanding outflow process)

Understanding outflow processes by identifying which types of plasma waves play the dominant role in accelerating ions to exceed escape velocities at the upper atmosphere.

(Objectives of Mission Goal-1)

Identify the small-scale characteristics of the coupling processes between space and the upper atmosphere using the simultaneous measurements of plasma waves, particle precipitation and auroral distribution from high-time and high spatial resolution observations obtained by two satellites flying in formation. Clarify the correspondence between small-scale and large-scale auroras and current system structures using high-temporal resolution observations, auroral imaging observations with a wider field of view than Reimei, and multi-scale observations with two satellites separating spatial and temporal variations.

The following sub-objectives are defined as specific science targets for Mission Goal-1

A: Cross-scale energy and mass couplings between the magnetosphere and ionosphere
B: Field-aligned acceleration of plasmas to drive the couplings
C: Generation of energetic electron precipitations and its relationship with the couplings

(Objectives of Mission Goal-2)

Clarify characteristics of plasma waves observed simultaneously with accelerated ions in order to reveal the efficient acceleration process of ions by the waves.

The following sub-objectives are defined as specific science targets for Mission Goal-2

A: Characteristics of plasma waves with long wavelengths associated with accelerated ions
B: Characteristics of plasma waves with short wavelengths associated with accelerated ions

Here, we define the long (short) wavelengths as waves with wavelengths longer (shorter) than a few hundred meters. For EMIC waves and long wavelength components of Alfven waves and BBELF waves, which are categorized as long wavelength waves here, interferometric analyses will be applied to electromagnetic field data obtained by multiple satellites operating closely together for the first time in the polar region. Although it is difficult to determine the wavelength of much longer than the inter-spacecraft distance, just showing that the Doppler shift for outflowing low-energy ions is negligible is sufficient to evaluate the possibility for ion acceleration. For shorter wavelength waves (ESICH waves, LH waves, and short wavelength components of Alfven waves and BBELF waves), whose wavelength could shorten down to a few tens of meters, interferometric analyses will be applied to monopole mode electric field data obtained by the tri-axial relatively short electric field sensors.

The Earth receives solar wind energy over a wide area exceeding 10 times the planetary radius due to the magnetosphere formed by the intrinsic magnetic field. Some of this energy enters the magnetosphere as plasma particles as well as electromagnetic energy. The plasma inflows to the upper atmosphere are largely concentrated in the cusp, which is the region where the magnetic field lines open toward interplanetary space on the day side of the polar regions, and in the auroral zones through the nightside magnetosphere. The multi-scale nature of the energy inflow is essential for the feedback from the atmosphere to space as well as energy dissipation shown as multi-scale aurora. The concentrated inflow of energy causes an intense plasma outflow, which contributes significantly to the mass supply to the magnetosphere as well as the atmospheric dissipation into interplanetary space. Although the atmospheres on magnetized planets are thought to be protected from the solar wind by their intrinsic magnetic fields, the effect of intrinsic magnetic fields is not simple and its long-term consequence for the atmospheric evolutions remains unclear. This is because that the interaction region between solar wind and magnetized planets would be wider than that of unmagnetized planets. In addition, a spatiotemporal concentration of energy inflow is expected to occur in the magnetized planets as described above.

FACTORS will address both the inflow and outflow of the coupling process: 1) interaction between the upper atmosphere and inflow from the space and 2) outflow from the Earth. The mission reveals the coupling process on the basis of detailed in-situ observations of the Earth, which is the only planet that can be relatively easily accessible and thereby detailed and comprehensive data sets are achievable. By clarifying the actual role of wave-particle interactions for both inflow and outflow, FACTORS demonstrates the importance of multi-scale process of energy inflow and atmospheric outflow, which need the kinetic treatment. The achievement of the mission goal brings about significant changes in our understanding about dynamics of plasma and atmosphere environments in the magnetized planets.

4.3 The compelling nature of the proposed mission concept and its relationship to past, current, and future other investigations and missions

The following points are unique observations provided by FACTORS that have not been achieved by past missions.

(Comprehensive Observations/Advantages over previous missions)

This mission will realize the simultaneous observations of electromagnetic fields, particles, and auroral emission with high-time and spatial resolutions, which has not been carried out in past missions such as FAST and Reimei, and will clarify the plasma acceleration process that produces small-scale aurora. In addition, we elucidate the relationship between small-scale and large-scale mechanisms of plasma acceleration by obtaining high-time resolution data equivalent to FAST and Reimei. Significant advantages of FACTORS are a much wider field of view of auroral imaging than Reimei, and in-situ data separated in time and space by two formation flight satellites. These are adequate to fill the gap between large-scale phenomena revealed by Akebono and small-scale phenomena obtained by Reimei. FACTORS will obtain the information about ion velocity distribution functions with unprecedented quality in the energy range from pre-accelerated to accelerated ions continuously with species discrimination, and capture processes by which (heavy) ions acquire the escape velocity at the key altitude region for ion outflows (1500–4000 km), where ion measurements themselves have not been performed for ~15 years since the retirement of the FAST satellite. (see Section 6.1 for details)

(Formation Flight)

Formation flight observation is essential to understanding the fundamental processes of plasma physics in near-Earth space as demonstrated by the past and present magnetospheric formation flight missions, such as recent ESA's Cluster project and NASA's MMS project. Formation flight observation is effective particularly for the magnetosphere-ionosphere coupling region where various acceleration mechanisms coexist over a wide range in temporal and spatial scales, and density and temperature of atmosphere as well as ambient magnetic field change drastically with altitude. However, no future mission in the world is currently planned to explore this region. FACTORS can provide unique, highly novel and original data that contribute to a universal understanding of particle acceleration mechanisms not only for the geospace but also in the solar atmosphere and magnetospheres in the solar system planets and exoplanets. (see Section 6.1 for details).

The FACTORS mission will realize formation flight observations by two small satellites. The distance between the satellites is ~10 km or less, which has never been achieved in past satellite projects in the magnetospheric and ionospheric explorations for polar regions. The ESA's Swarm satellite launched in 2013 has been operated for the multi-satellite observation of the upper atmosphere. However, the primary purpose of the Swarm satellite was to measure the global magnetic field, and the Swarm constellation is not capable of measuring plasma particles which are responsible for the auroral emission. Elementary processes of the plasma particle acceleration are vital for understanding the coupled solar-space-Earth system, and comprehensive observations of plasma particles, waves, electromagnetic fields, and auroral emissions are requisite. FACTORS will also derive the frequency and wavelength of plasma waves, and identify which modes of waves contribute to various scales of auroral structure.

(Wave-Particle Interaction Analyzer)

To directly prove ion acceleration, FACTORS team will apply the method of Wave-Particle Interaction Analyzer (WPIA), which the Japanese group has an advantage [e.g., Katoh et al., *Earth Planet Space* 2018; Kitamura et al., *Science*, 2018; Shoji et al., *Sci. Rep.* 2021; Asamura et al., *Phys. Rev. Lett.*, 2021; Kitamura et al., *Nature Comm.*, 2022], to the obtained electromagnetic field waveform data and ions (especially data obtained by an ion energy-mass spectrometer (SIMS-G) focusing on the gyration phase angle distribution). (see Section 6.1 for detail).

(Interferometric observations)

FACTORS will realize the observation of six components of the electromagnetic field for plasma waves (especially electromagnetic modes that are expected to have long wavelengths), and determine the direction of propagation and wavelength of the waves by interferometric observations between satellites. These observations will provide critical information to identify the mode of electromagnetic waves (and almost static spatial structures) and their contribution to ion acceleration. (see Section 6.1 for detail).

(Contribution to Future Project)

FACTORS is the first Japanese formation flight mission to explore the geospace, and therefore, the realization brings us both of scientific knowledge and technologies gained through the project, which contributes to future satellite missions. For example, toward the ultra-multipoint nano-satellite observations in the near-Earth space, which is currently under consideration, FACTORS plays a significant role not only in scientific outputs but also in engineering aspects, such as flight dynamics and satellite operations. Concerning general understandings of the universal space plasma acceleration mechanism, FACTORS will not only promote the ongoing planetary missions to Jupiter, such as NASA's Juno and ESA's JUICE, but will also enrich and deepen the scientific outputs from the future explorations of Jupiter, Saturn, Uranus, Neptune, magnetized satellites and small bodies, which have not been explored yet.

5 Launch date constraints

5.1 Schedule impact on science [18-3-1]

The launch of FACTORS is targeted for the mid FY2032. In that case, a rough development schedule and a time table of detailed schedule are shown in **Table 5.1-1** and **Fig. 5.1-1**, respectively.

5.2 Schedule impact on science [18-3-1]

The FACTORS mission aims to address fundamental physical mechanisms controlling the space-Earth coupling system. Although the desirable space condition for FACTORS is not restricted dominantly by the solar activity or the other causes/effects, it would be more scientifically important that FACTORS makes advanced/innovative observations during some high physical activities and processes occurring in the terrestrial magnetosphere and ionosphere than under extremely low conditions.

Because the targeted observation period during 2032-2033 corresponds to the rising phase of the 11-year solar cycle, the schedule delay of several years does not significantly affect the scientific achievements. Some more detailed viewpoints regarding the science impacts caused by schedule delays are summarized below.

1. The goal of this mission is to quantitatively observe the elemental physical processes in the space-Earth coupling system, and it is expected that there will be no significant dependence of the mission achievements on the solar activity period if the nominal science observation operations can be secured for at least one year after the commissioning phase (initial instrument check period). On the other hand, it would be better to survey the physical processes over a wide range of the solar activity. FY2032 is the rising phase of the solar activity, which corresponds to a period of the rapid increase in the solar activity, making it easier to investigate the dependence on solar activity for a short term.

Table 5.1-1. Rough development schedule of FACTORS.

Submit mission proposal	FY2022 Q2
Review by Advisory Committee for Space Science	FY2022 Q3
Mission definition phase start review	FY2023 Q2
International review	FY2025 Q1
Mission definition review (MDR)	FY2025 Q3
Pre-project AO, selection	FY2025 Q4
System requirement review (SRR)	FY2025 Q2
RFP	FY2025 Q4
ISAS-SNSA joint system requirement review (SRR) (option)	FY2025 Q3
System definition review (SDR)	FY2027 Q3
Trans-project review	FY2027 Q4
MTM preliminary design review(MTMPDR)	FY2028 Q2
SI preliminary design review （IPDR)	FY2028 Q3
Preliminary design review (PDR)	FY2028 Q4
MTM critical design review (MTMCDR)	FY2028 Q4
SI critical design review (ICDR)	FY2029 Q3
Critical design review (CDR)	FY2029 Q4
Pre-shipment review （PQR/PSR)	FY2031 Q4
Launch readiness review (LRR)	FY2031 Q2
Launch site integration/operation	FY2032 Q1-Q2
Launch	FY2032 (July-August)

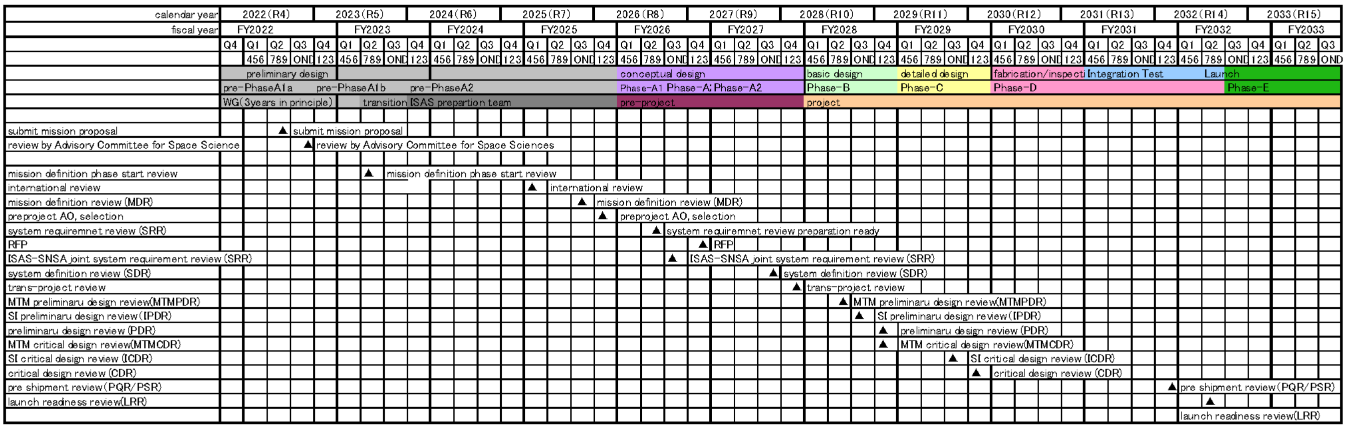

Fig. 5.1-1. Time table showing detailed schedule of FACTORS.

2. Except during periods of extremely low solar activity, the phenomena that can be measured by the FACTORS satellite's science instruments are expected to occur within a few percent of the observation time, allowing the extraction of physical processes. For example, auroral acceleration phenomena are always present even during the 1-2 year period of solar minimum activity, but the probability of the appearance of quickly varying fine-scale auroras is reduced by half. Although this reduces the number of observation opportunities, it does not pose a problem for the extraction of physical processes by the FACTORS observations. Therefore, even a delay of two to three years from the original plan does not correspond to the period of an extremely low solar activity, and the science objectives are considered achievable. On the other hand, there are concerns about the impact of an 8-year delay from the original plan (e.g., launch delayed form FY2032 to FY2040). Since such a huge delay is unlikely and some auroral activities are always present in principle, there is sufficient time to develop and launch the satellite.
3. If the launch is delayed by two to three years, it corresponds to a period of high solar activity, and the probabilities of auroral phenomena and atmospheric outflows with various sizes and forms will increase, but the complicated mixtures of elementary physical processes related to the energy/mass transports in the space-Earth coupling systems may require careful and advanced analysis treatments to extract the elemental processes from the observations.
4. The high solar activity increases the atmospheric density in the Earth's upper atmosphere, which increases the atmospheric drag as an aerodynamic effect on satellites. In addition, the difficulty of controlling and maintaining the formation flights may increase due to fluctuations in the upper atmosphere in response to relatively short-term (several 10 minutes to a few weeks) changes in the space environment, such as substorms and space storms, requiring careful consideration.

The mission life in the FACTORS satellite development plan is assumed to be one year, the same as the ERG mission. Since the manufacturer in charge of the FACTORS satellite bus system has not been determined at this time, the full consistency between mission life and cost has not been made yet. Therefore, this proposal presents a plan to achieve the science objectives within one year after launch.

6 Scientific investigations of the mission [3-2–1]

Science questions and requirements are summarized in **Table 6-1**. RS means the science requirement, which indicates necessary observations to understand each science question. Science requirements and instrument performance requirements (RI) are summarized in **Table 6-2**. Brief explanations about RS and RI are listed in the following paragraphs. As shown in these tables, studies of the aurora and ion outflows require data from the same instrumentation in many aspects.

Low-frequency fields/waves observations

To resolve electric and magnetic field variations at the ULF-VLF (~a few Hz ~ 10 kHz) frequency range (**RS-1**), sufficient frequency coverage is necessary. The most important wave for auroral phenomena is Dispersive Alfven Wave (DAW) which accelerates electrons in the field-aligned directions, and important waves for ion acceleration are ElectroMagnetic Ion Cyclotron (EMIC) waves, Alfven waves, Broad-Band ELF (BBELF) waves, solitary waves, ion acoustic waves, Broadband Electrostatic Noise (BEN), and Electron Cyclotron Harmonic (ECH). To resolve how these waves cause accelerations of electrons and ions, the electric/magnetic field measurements are necessary. To satisfy the requirement of RS-1, the waveform measurements by electric field antenna and flux gate magnetometer should observe waves at the ULF-VLF range (**RI-1**). To discriminate spatial-temporal variations of the waves and static structures, multi-point observations by two satellites are necessary. Moreover, interferometric observations of electric fields can be applied to resolve characteristics of the waves (**RS-11, RI-12, Fig. 6-1**).

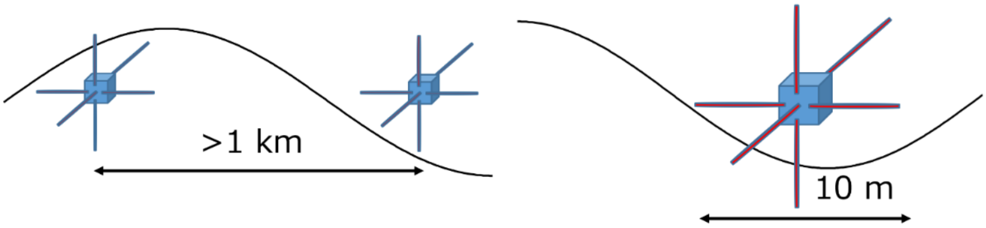

Fig. 6-1. Conceptual pictures of (left) the multi-satellite interferometric observations for long wavelength waves (inter-spacecraft phase difference) and (right) the interferometric observations for short wavelength waves with monopole observation of electric fields (phase difference between sensors on opposite side of the satellite).

High frequency electric field measurements

To observe the Upper Hybrid Resonance (UHR) waves that can provide the ambient plasma density and several radio waves, e.g., Auroral Kilometric Radiations (AKRs) emitted from the accelerated electrons (**RS-2**), the measurements of plasma/radio wave frequency spectrum at high-frequency range (HF) are necessary (**RI-2**).

Field-aligned current (FAC) observations

To resolve net energy input to the upper atmosphere as the upward/downward current, the measurements of FAC are necessary (**RS-3**). To satisfy the requirements of **RS-3**, the measurements of the magnetic field vector are necessary (**RI-3**).

Poynting flux observations

To resolve net energy input to the upper atmosphere as the electromagnetic waves, the measurements of the Poynting flux are necessary (**RS-4**). Poynting flux as the wave energy of the Alfven waves must be compared to the particle kinetic energy to understand the particle acceleration process. The fundamental waves to carry the Poynting flux are Alfven waves. These measurements are also important to determine the propagation direction of EMIC waves for clarifying the resonance condition with ions. To satisfy the requirement of **RS-4**, the measurements of electric and magnetic fields at the ULF-VLF frequency range are necessary (**RI-1**).

Field-aligned accelerated electron observations

To resolve net energy input as filed-aligned accelerated electrons, the measurements of the electron flux with relevant time resolutions better than 20 msec and angular resolutions better than 25° are necessary (**RS-5**) [Motoba and Hirahara, *J. Geophys. Res.*, 2016]. This is also necessary to understand which region the satellite is located (auroral zone, cusp, etc.). To satisfy the requirement of **RS-5**, the measurements of the electron flux as a function of pitch angles and energies from a few tens eV to a few tens keV are necessary (**RI-4**). Ambient magnetic field observations are also needed to determine the pitch angle (**RI-1**).

Scattered electron observations

To resolve net energy input as high-energy electron precipitation via the pitch angle scattering, the measurements of the electron flux at a few tens keV to ~ 1 MeV with relevant time resolutions are necessary (**RS-6**). To satisfy the requirement of **RS-6**, the measurements of the precipitating electron fluxes with energies from a few tens keV to ~1 MeV are necessary (**RI-5**). Ambient magnetic field observations are also needed to determine the pitch angle (**RI-1**).

Ion flux observations

To detect accelerated and pre-accelerated ions for outflows, ion measurements with species discrimination are necessary with angular resolutions better than 25° with temporal resolutions of ~100 (500) msec for the energy range above (below) 10 eV (**RS-7**). **RS-7** also satisfies requirements about the field-aligned potential drop; the measurements of the upward ions as a counter part of downward electrons. To satisfy the requirement of **RS-7**, the measurements of ion flux as a function of the pitch angle and energy from ~1 eV to a few tens of keV are necessary (**RI-6**). Ambient magnetic field observations are also needed to determine the pitch angle and gyration phase angle (**RI-1**). To observe heavy ions coming from the ram direction (the direction opposite to the satellite motion, i.e., relative velocity seen from the satellite), ion spectrometers with deflectors, which provides wider field of views, are necessary (**RI-13**). It is also an important observation for understanding of the dispersion relation of waves, especially EMIC waves.

Ambient density measurements

To resolve characteristic of DAW that contributes to the field-aligned accelerations and investigate dispersion relations of waves, the density resolution should be accurate better than 1% or 0.1 /cm3, whichever is worse (**RS-8**). To satisfy the requirement of **RS-8**, the measurements of the high-frequency electric field that covers UHR at the HF frequency range with a time resolution less than 1 sec are necessary (**RI-7**). Ambient magnetic field observations are also needed to derive the density (**RI-1**). The satellite potential measurements can also be used to estimate ambient density (**RI-10**).

Auroral images

To resolve the spatial scale of energy input from the magnetospheres to the upper atmosphere and to estimate 2D spatial distributions of characteristic energy and total energy input of precipitating electrons, imaging observations with relevant spatial resolution and field of view are necessary (**RS-9**). To satisfy the requirement of **RS-9**, a spatial resolution better than 1 km × 1 km and a field of view of at least 500 × 500 km (**RI-8**) are needed. To achieve longer-time imaging measurements, observations under the condition of a satellite exposed to the sunlight are important. To realize this requirement, observations at ultra-violet wavelength are needed (**RI-9**). A conceptual picture about comprehensive observations with field/waves, plasma particles and imaging that are realized by the FACTORS mission is shown in **Fig.6-2.**

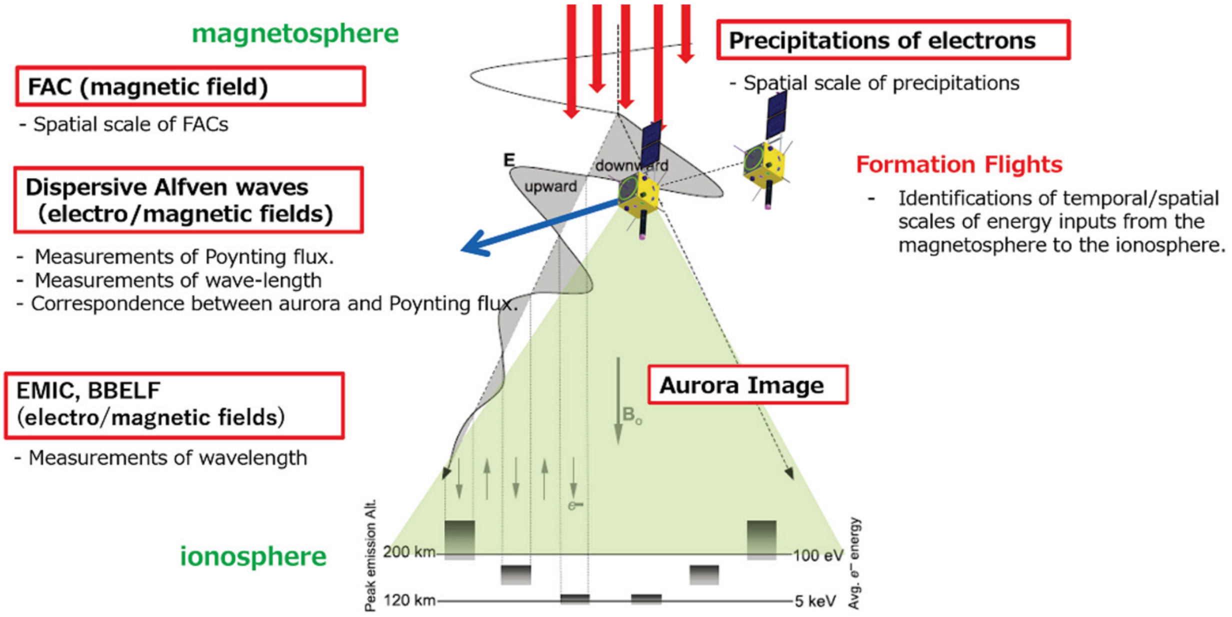

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Fig. 6-2. Conceptual picture of the formation flights and simultaneous observations of particle, and imaging.

Ion measurements for WPIA

To try to get direct evidence of energy transfer from the waves to ions with the method of WPIA, synchronized measurements of ion fluxes with wave fields are necessary (**RS-12**). Time tags with accuracy better than ~100 μsec relative to the electromagnetic field waveform data should be added to ion data (**RI-14**). The method of WPIA will be applied to downlinked data.

Requirement for orbit

(Apogee altitudes) Main targets of FACTORS are aurora phenomena as an energy input and ion outflow processes. These phenomena mainly occur around the altitudes from 1000 km to 4000 km, so the apogee of the satellites should be 3500–4000 km to realize the maximum opportunities of the necessary observations.

(Inclination angle) The inclination angle should be considered to cover polar ionosphere including auroral oval, cusp and polar cap. Currently, the planned inclination angle of the satellite orbit is ~70° –90°.

(Launch condition) Auroral imaging measurements on the aurora are possible in the winter season, so initial observations should be optimized in the winter season of the northern hemisphere. So, the suitable launch interval will be around the fall equinox.

Requirement for inter-spacecraft distance

The inter-spacecraft distance of FACTORS is considered to resolve plasma waves that causes the meso-scale/fine-scale structures of aurora. From the ground-based optical measurements, typical scale sizes of the aurora stripes and spacing between them to be on average 13–14 km are reported [Axelsson et al., *Ann. Geophys.*, 2012]. Considering previous observations and possibility to find further small-scale phenomena, the inter-spacecraft distance less than 10 km is required for this mission.

Table 6-1. Science Questions and Required Science.

Science Questions		RS-1 (Plasma wave)	RS-2 (High frequency wave)	RS-3 (Field aligned current)	RS-4 (Poynting flux)	RS-5 (Electron flux)	RS-6 (High-energy electron flux)	RS-7 (Low-energy ion)	RS-8 (Electron density)	RS-9 (Auroral image)	RS-10 (Satellite potential)	RS-11 (Wavelength measurements (short))	RS-12 (Synchronized measurements of ion and waves)
Mission Goal-1: Understanding inflow process	A: Cross-scale energy and material couplings between the magnetosphere-ionosphere	✔	✔	✔	✔	✔		✔	✔	✔			
	B: Field-aligned acceleration of plasmas to drive the couplings	✔		✔		✔		✔	✔	✔	✔		
	C: Generation of energetic electron precipitations and its relationship to the couplings	✔				✔	✔	✔	✔	✔	✔		
Mission Goal-2: Understanding outflow process	A: Characteristics of plasma waves with long wavelengths associatied with acceleratied ions	✔	✔		✔	✔		✔	✔		✔		✔
	B: Characteristics of plasma waves with short wavelengths associatied with acceleratied ions	✔	✔		✔	✔		✔	✔		✔	✔	✔

Table 6-2. Required Science and Required Instruments.

Science Measurement Requirement	Instrument Performance Requirement
RS-1 Observation of electric and magnetic field waveforms in the ULF–VLF frequency band to investigate detailed plasma wave features.	**RI-1** Observation of six components of electric and magnetic field waveforms in the frequency range of ULF to VLF using electric field sensors, search coil magnetometers and fluxgate magnetometers on two satellites.
RS-2 Observation of electric field spectra in the wide frequency range to detect high-frequency plasma and radio waves.	**RI-2** Observation of electric field spectra in the HF frequency range using an electric field sensor. The target waves are AKRs and UHR waves.
RS-3 Observation of magnetic field in the ULF–ELF frequency band to derive the filed aligned current.	**RI-3** Observation of magnetic field waveforms in the frequency range of ULF to 100 Hz using a fluxgate magnetometer.
RS-4 Observation of electric and magnetic fields in the ULF–ELF frequency band to calculate the Poynting flux.	**RI-1** Observation of six components of electric and magnetic field waveforms in the frequency range of ULF to VLF using electric field sensors, search coil magnetometers and fluxgate magnetometers on two satellites.
RS-5 Observation of precipitating electron energy spectra and pitch angle distribution.	**RI-4** Observation of electron flux and pitch angle distribution in the energy range from 10 eV/q to 30 keV/q with a time resolution less than 20 msec using an energy analyzer.
RS-6 Observation of high-energy precipitating electron energy spectra and pith angle distribution.	**RI-5** Observation of precipitating electron flux in the energy range from 10 keV to 1 MeV with temporal resolution about a few tens msec using a semiconductor detector.
	RI-11 Observation of electric field waveform that covers the VLF frequency range (<20 kHz) using electric field sensors.

RS-7 Observation of supra-thermal and low-energy ion energy spectra and pitch angle distribution with ion species discrimination.	**RI-6** Observation of ion flux and pitch angle distribution in the energy range from ~1 eV/q to 25 keV/q with a time resolution of ~100 msec (~500 msec for <10 eV) using energy-mass spectrometers.
	RI-13 Observation of heavy ions from the ram direction by ion energy-mass spectrometers with deflectors.
RS-8 Electron density observation with 1% accuracy.	**RI-7** High frequency electric field observation using electric field sensors or observation by a Langmuir probe. UHR wave measurements (RI-2) are also available to measure the electron density.
RS-9 Continuous imaging observation of the two-dimensional distribution of visible/FUV aurora using two sensors sensitive to visible and FUV.	**RI-8** Visible aurora observation with following requirements: Field of view: ~500 km × 500 km at 4000 km altitude Wavelength: N2 1PG (~670 nm) Spatial resolution: ~ 1 km × 1 km Temporal resolution: a few Hz
	RI-9 FUV aurora observation with following requirements: Field of view: ~500–1000 km × 500–1000 km at 4000 km altitude Wavelength: 130–180 nm Spatial resolution: less than ~ 5 km × 5 km Temporal resolution: a few Hz
RS-10 Observation of satellite potential.	**RI-10** Observation of electric field in the low frequency range or observation by a Langmuir probe with a time resolution less than 500 msec.
RS-11 Measurements of plasma waves with wavelength between few tens of meters and several hundreds of meters	**RI-12** Interferometric measurements of electric fields with electric field monopole observations with tri-axial relatively short electric field sensors.
RS-12 Synchronized measurements of ion fluxes focused on accelerated ions with wave fields	**RI-14** Species discriminated ion data production focusing on the selected directions, which should have time tags with accuracy better than ~100 µsec relative to time tags of the waveform data of plasma waves.

6.1 Rationale for the investigations [3-2-2][1-3-1]

As shown in Section 14, a number of heritages of past Japanese geospace/planetary satellites will be implemented in the FACTORS mission. And we have investigated the feasibility about the newly developed objectives based on computer simulations and brief estimation from the previous observations. (1) simultaneous observations between auroral imager and particle measurements, and (2) plasma wave measurements by two-satellites, (3) wave-particle interaction analyzer and measurements of ions coming from ram direction. The initial estimations are shown below, indicating feasible of these points. And rationale about the apogee altitude is also shown.

6.1.1 Apogee altitude

While accelerated ions have been reported even at altitudes lower than ~1000 km in the nightside auroral zone, ions that exceeded escaping energy (~10 eV for O^+) near the dayside cusp have been observed mainly at altitudes higher than ~2000 km [e.g., Miyake et al, *J. Geophys. Res.*, 1993; Bouhram et al. *Ann. Geophys.*, 2004]. It has been pointed out that there may be differences in the acceleration process in different regions. Thus, to comprehensively understand the processes by which heavy ions acquire the energy necessary for outflow in the cusp and auroral zone, it is essential to cover altitudes up to well above 2000 km. Since no information at higher altitudes than the apogee of the satellite can be estimated for studies on ion outflows, a higher apogee is preferable from this point of view. In contrast, a satellite in sunlight is positively charged in regions of low plasma density at high altitude, which prevents low-energy ions from reaching the satellite. It is desirable for the FACTORS mission to concentrate its observations at altitudes where large positive charging does not occur frequently. On the basis of the FAST satellite observations, it is expected that there will be sufficient time without large (>1 V) positive charging below ~4000 km altitude. Thus, an apogee altitude of 3500–4000 km was determined to maximize the outcome.

6.1.2 Simultaneous observations between auroral imaging and particle measurements

The feasibility of simultaneous auroral imaging and particle observations was investigated by analyzing various satellite orbital conditions. **Fig. 6.1.2-1** schematically shows the satellite coordinate system and the positions of the instruments relative to the satellite. The four conditions for simultaneous observation to be valid are: (1) the particle observation covers the full pitch angle, (2) the field of view of the auroral imager includes the satellite footprint, (3) the sun angle is within 20°, and (4) the satellite footprint is not exposed to the sunlight. For orbital parameters of the satellite, we have investigated the following parameter range:

Epoch: Sep. 21, 2030, 00:00:00UT (the latest target launch year is 2032)
Apogee altitude: 4000 km (the latest target altitude is 3500 km)
Perigee altitude: 400 km (the latest target altitude is 350 km)
Inclination: 70°–90°
Argument of perigee: 150°–180°
Right ascension of ascending node: 0°–360°
True anomaly: 0°

In addition, the imager's line-of-sight angle was set as 40°. As a result, it was found that there are more than 350 hours (about 2% of the total observations) in which the simultaneous auroral imager and particle observations can be realized in two years (**Fig. 6.1.2-2**). Considering the Alfven waves, which generate auroral fine structures, this observation time is comparable to that of the Reimei satellite (640 km altitude in a quasi-sun-synchronous circular orbit at 00:50–12:50 local time). This indicates that the observation time is sufficient to achieve the goals of this mission.

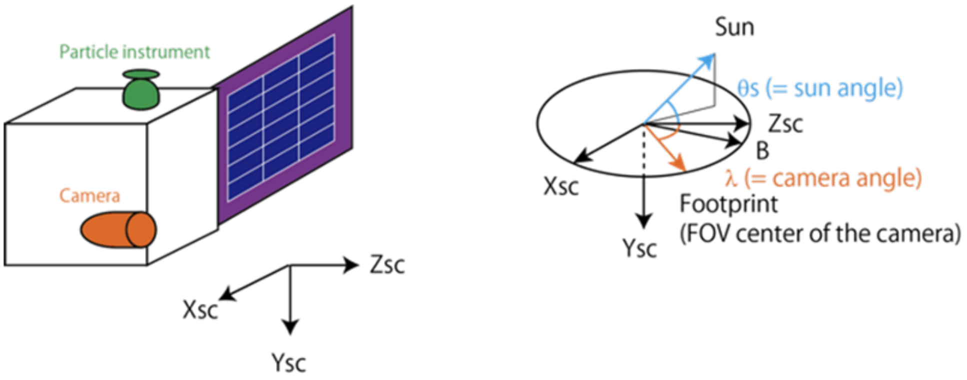

Fig. 6.1.2-1. Satellite coordinate system and positions of instruments used to examine the feasibility of simultaneous auroral imager and particle observations, where Xsc, Ysc, and Zsc are the satellite 3-axis attitude, λ is the angle between the imager's field of view center and the satellite Z axis, and θs is the Sun angle.

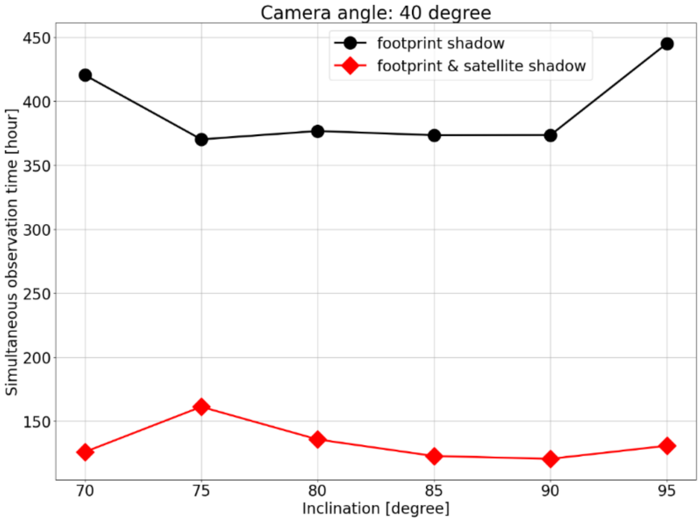

Fig. 6.1.2-2. Total time to meet the conditions for simultaneous auroral imager and particle observations over a two-year period starting in 2030 in orbits with perigee and apogee of 400 km and 4000 km, respectively (target orbits with 350 km perigee and 3500 km apogee for the launch in September 2032). Black: footprint in eclipse (night); red: both footprint and satellite in eclipse (night).

6.1.3 Multi-satellite interferometric observations

We investigated the feasibility of deriving the frequency and wavelength of propagating plasma waves by two FACTORS satellites. In this study, time series data of waveforms observed by the two satellites based on planed FACTORS orbit conditions was used. We assumed pseudo plane waves for Alfven waves that would be observed by the FACTORS satellites in the polar regions. Actual Alfven waves are plane waves with a finite frequency range, but here we assumed monochromatic waves. The initial configuration of the two FACTORS satellites at the apogee (altitude of 3500 km) were set to three conditions: 10 km apart horizontally, 10 km apart along the orbit, and 10 km apart vertically. Assuming monochromatic waves of realistic amplitude and wavelength (wavelength assumed to be 10–100 km), pseudo-observational data of the three components of the magnetic fields of the two satellites were generated. An analysis algorithm called the Means method was applied to the data to derive the direction of propagation of the given wave, i.e., the wavenumber vector. The instantaneous phase was obtained by applying the Hilbert transform to the magnetic field waveforms observed by the two satellites. Using the derived instantaneous phase and the previously derived wavenumber vector and inter-spacecraft distance vector, we established a method for deriving the frequency and wavelength of waves in an inertial system. The left panel in **Fig. 6.1.3-1** is a schematic of observations by the two FACTORS satellites, showing the wave propagation direction (wavenumber) vector k and the inter-spacecraft distance δx. The right panels of **Fig. 6.1.3-1** are a frequency-time diagram for the three observed magnetic field components, power spectrum, polarization, and propagation angle of the derived wave.

The results derived from this method were examined for Alfven waves with several wavelengths and frequencies. The results show that the derivation of wave frequencies and wavelengths is possible for the above three initial configuration conditions of the two FACTORS satellites. In conventional single-satellite observations, it was necessary to assume a dispersion relation of plasma waves in order to derive the wavelength and frequency of the observed waves. On the other hand, by using data from two satellites, it was shown that it is possible to derive the wavelength and frequency of the single-wavelength Alfven wave and to identify the mode of the wave without assuming the dispersion relation of the plasma wave. However, it was found that the derivation was limited by the angle between the wave propagation direction vector and the distance vector between satellites. In the future, we will examine whether it is possible to derive the wavelength and frequency of each wave when multiple Alfven waves are overlapped. We are currently conducting a Monte Carlo study of the case where two Alfven waves are overlapped and have confirmed that in some cases the two waves can be properly reconstructed using the method we have developed. It has also been found that the accuracy of wave estimation depends on the angular difference between the velocity vector of the satellite and the wavenumber vector, as well as on the frequency difference between the two waves.

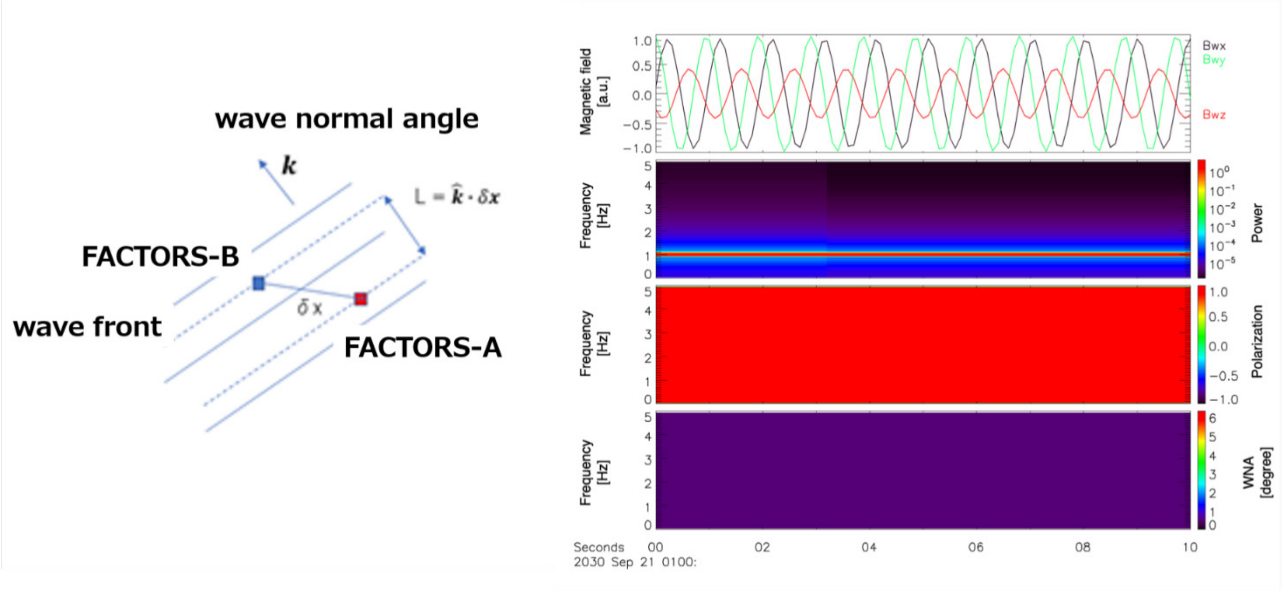

Fig. 6.1.3-1. Left: conceptual view of multi-satellite interferometer observations by FACTORS-A and B. Right: From top to bottom: 3-dimensional magnetic field observed by virtual satellites. Frequency spectrum, polarization and wave normal angle.

6.1.4 Ion measurements of SIMS-G for wave-particle interaction analyzer (WPIA) and special measurements

Although newly accelerated ions are concentrated close to a pitch angle of 90°, it is necessary to place ion energy-mass spectrometers (LIMS, SIMS) so that they cover the entire pitch angle to obtain overall velocity distribution functions. An additional ion energy-mass spectrometer that concentrates on measurements of accelerated ions close to a pitch angle of 90° and allows simultaneous observations of ions at various gyration phase angles will be installed (SIMS-G). The 360° planar field-of-view of SIMS-G is configured to be orthogonal to that of LIMS and SIMS, so that the gyration phase angle around 90° pitch angle can be covered by ~16 sectors of SIMS-G in a certain time by satellite attitude control. Since ions are mostly concentrated slightly upward from a pitch angle of 90°, the field of view is adjusted with a deflector in SIMS-G. By limiting the energy range and number of steps of SIMS-G, it is possible to increase the ion counts per unit time by a factor of >100 for a part of the distribution function. The count rates of SIMS-G per sector become ~2000 /sec for events with intense fluxes (10^7 eV/(cm^2 sr s eV)). Identifying nongyrotropy (existence of enhancement or depression of fluxes at a certain gyrophase angle) rotating with the wave field is a key feature for analysis using the method of WPIA [Kitamura et al., *Science*, 2018; Kitamura et al., *Nature Comm.*, 2022]. An initial analysis indicated that 30% enhancement of the flux at a certain gyration phase angle relative to the wave field provides meaning results within ~1 sec in each sector. By combining multiple sectors, such detection will become possible within shorter interval or smaller nongyrotropy will become discriminable.

When the attitude of the satellite is not suitable for WPIA or when burst observations are not performed, SIMS-G will be used to observe ions from ram direction (ram mode) or accelerated ions around 90° pitch angle with high pitch angle resolution (<10°) (perp mode), which cannot be established by LIMS or SIMS, and much better than ion energy-mass spectrometer on the FAST satellite. At the polar region where the velocity vector of the satellite tends to become close to perpendicular to the magnetic field, the field-of-view of SIMS-G become suitable for observations of ram ions. O^+ ions with zero energy in the frame fixed to the Earth is observed as ram ions with energy from 2–5 eV due to the motion of FACTORS. Since there is bulk flow of plasma, the plasma rest frame shifts a little from the frame fixed to the Earth. Observation of ram mode thus provides important information to determine the origin of the plasma drift frame, which is the frame that the bulk motion of plasma perpendicular to the magnetic field is canceled, and to convert the ion energy observed by the satellite into energy in the frame. Perp mode observations provide detailed information on how close to 90° the ion pitch angle is, which corresponds to how close to the satellite altitude the acceleration is occurring. Around the apogee, ions moving within 10° from 90° pitch angle are accelerated within 100 km in altitude. This increases to 500 km if 22.5°, which is the resolution of usual ion energy-mass spectrometers, from 90° is used for the same estimation.

6.1.5 Wave and ion measurements for interactions between short-wavelength waves

Electrostatic waves represented by the ESICH wave and LH waves are candidates for accelerating ions through wave-particle interactions. Such electrostatic waves have relatively shorter wavelengths than electromagnetic waves. Since the order of the wavelengths could range from a few tens of meters to a few hundreds of meters, frequently used long electric field sensors with lengths of a few tens of meters are at a disadvantage in quantitatively precise observations. FACTORS's 5 m electric field sensor is appropriate for measuring electrostatic waves with short wavelengths as well as electromagnetic waves with long wavelengths.

Meanwhile, the smallest-spatial scale events associated with ion acceleration are Lower Hybrid Solitary Structures (LHSS), which are reported to be ~20 m in diameter at altitudes of ~500–1000 km (existence above 1000 km is a subject to study). A time resolution of ~2 msec for ion measurements is required to resolve this structure. However, such high time resolutions are not feasible with usual ion energy-mass spectrometers. In this mission, while observing the overall picture of the distribution function by LIMS and SIMS, we will try to detect ion flux variations by ultra-short time ion acceleration (=small scale in plasma rest frame) associated with LHSS by performing the SIMS-G LIST mode observation with the fixed energy step mode described above.

7 Instrumentation of the mission and mission data [5-2–1]

7.1 One sentence description of the technology to realize the investigations [5-2-1]

In-situ observations of plasma particles and waves with high-time resolution are performed simultaneously at multiple points within a spatial scale of the energy inflow via particle precipitation and electro-magnetic field and particle outflow due to ion acceleration, as well as auroral imaging observations of auroral fine structures over a wide area by auroral imagers onboard the satellite.

7.2 Comparisons of the selected technology with other technologies [5-2-2]

7.2.1 Plasma particle measurement

A top-hat type electrostatic energy-per-charge analyzer, which was invented in the late 1980s for in-situ measurements of plasma particles in space, has been improved and has been used on many satellite missions. The top-hat analyzer has the advantages of (1) a planar field-of-view, (2) a detector with a flat input surface can be used for resolving incoming direction of particles, and (3) high sensitivity relative to the size of the instrument. The top-hat type analyzer is suitable for missions such as FACTORS that require high time resolution, because it can provide the high sensitivity, and the simultaneous coverage of full pitch angles when the local magnetic field direction is captured in its field-of-view. Note that a mass analysis section can be easily connected to the rear stage of the top-hat type analyzer, and this configuration has a number of achievements as an ion energy-mass spectrometer in space missions.

In order to achieve simultaneous particle, plasma wave, and auroral imaging observations, it is basically necessary to observe particles with full solid-angle coverage. The Magnetospheric MultiScale (MMS) mission (NASA) carries a large number of identically designed ion instruments (8 instruments per satellite) to cover all the directions and observe the ion distribution resolving not only the pitch angle but also gyration phase of ion cyclotron motion with high time resolution. However, this method is not realistic for FACTORS because it requires a lot of resources (the total mass of the low-energy electron and ion instruments onboard MMS is approx. 55 kg, which is almost the same as the total weight that can be allocated to the scientific instruments onboard FACTORS). The Reimei satellite, on the other hand, has succeeded in efficiently implementing opportunities for simultaneous particle and auroral imaging observations by proper field-of-view layout of the particle analyzer and the auroral imager. The same method will be applied to FACTORS to optimize simultaneous particle and auroral imaging observations.

Ions accelerated in the perpendicular direction of the magnetic field lines is one of the important observation targets in FACTORS. When the satellite attitude conditions are favorable, simultaneous measurement of the pitch angle distribution and gyration phase distribution of ions can be performed by installing two or more ion energy-mass spectrometers in an orthogonal arrangement. Furthermore, while continuous observation over a wide energy range is required for the measurement of the pitch angle distribution of ions, the gyration phase distribution is worth observing even when limited to the energy range where there are many accelerated ions. It is estimated that the ion count rate in the perpendicular direction of the local geomagnetic field can be up to 100 times higher than those of existing analyzers (for the particular energy and pitch angle of interest) by limiting the measurement energy range and increasing the count rate by observing all the gyration phase directions simultaneously. FACTORS carries two supra-thermal ion energy-mass spectrometers (SIMS and SIMS-G) which are located in the orthogonal arrangement on the satellite to perform the simultaneous measurement of the pitch angle distribution and gyration phase distribution of ions.

7.2.2 Auroral imaging

Auroral emission has been observed from the ground using all-sky cameras. However, a ground-based camera has a limited field of view, and observation is affected by weather conditions, generally poor in the polar region. Auroral emission is extending almost vertically from 100 km to 400 km altitude range. The distance between the ground and auroral emission layer is too close to separate the auroral structure extending vertically due to the overlapping along a line-of-sight direction. Thus, it is extremely difficult to observe the auroral fine structure from the ground cameras. For this reason, despite many attempts to simultaneous and coordinated observations of aurora between ground cameras and in-situ satellites measurements, data of satisfactory quality were rarely obtained so far.

The auroral imager MAC on Reimei demonstrated the effectiveness of satellite-installed auroral imaging observations of 1-km scale fine auroral distributions and simultaneous particle measurements. However, Reimei was a lower-earth-orbit satellite with a limited imaging field of view, and no electromagnetic field measurements were installed. Auroral imaging observation at high altitudes like FACTORS is essential to cover a wide field of view, and it is necessary to visualize the two-dimensional distribution of transport of particles and electromagnetic field energy associated with auroras, and their dissipation in the ionosphere.

On the other hand, in many cases FACTORS will observe with sunlit satellite conditions near the apogee, in which visible auroral observation is not possible due to strong contamination caused by solar scattered light. Although far-ultraviolet auroral intensity is a few to several times smaller than that of visible aurora, solar irradiance in the far-ultraviolet range is ~10,000 times fainter than that in the visible range. This allows us far-ultraviolet auroral observation even in the sunlit conditions. For above reason for observations in visible and far-ultraviolet ranges, two imagers will be installed on FACTORS: one is a visible imager that captures visible aurora at highest time and spatial resolutions, although it operates only in the eclipse region. Another is a far-ultraviolet imager that observes in the both of sunlit and eclipse regions, where observation opportunities are more frequent, although the resolutions or S/N is not good as the visible imager.

7.2.3 Simultaneous observation of particles, plasma waves, and auroral images

Japanese Reimei satellite is a unique example of a satellite that has performed simultaneous particle and auroral imaging observations in the past [e.g., Ebihara et al., *J. Geophys. Res.*, 2009, Asamura et al., *Geophys. Res. Lett.*, 2009]. Reimei made more than 1500 simultaneous particle and imaging observations in three years, but it did not observe plasma waves, and its low altitude orbit limited the area covered by the onboard auroral imager to relatively small size. On the other hand, the FAST satellite achieved simultaneous particle and plasma wave observations over the auroral region with high-time resolution, but did not carry auroral imagers. FACTORS will be the first satellite mission to realize simultaneous observations of particles, plasma waves, and auroral images. As shown in Section 6.1, the feasibility of simultaneous particle-auroral imaging observations was studied by exhaustively changing orbital parameters at apogee altitudes of 4000 km and perigee altitudes of 400 km, and it was found that simultaneous observations were possible for about 2% of the total flight time (simulation period: 2 years). This value is comparable to the observation probability of Reimei (640 km altitude, quasi-sun-synchronous circular orbit at 00:50–12:50 local time), which indicates that the observation time is sufficient to achieve the goals of FACTORS mission.

7.2.4 Electric field and plasma wave measurement

FACTORS performs a complete set of electromagnetic field observations that simultaneously captures three components of the electric field and three components of the magnetic field. Until now, Japanese satellites have lacked one electric field component because they did not have an electric field sensor for the spin axis direction. However, FACTORS combines a newly developed tri-axial electric field sensor with conventional search coil magnetometers to capture the electromagnetic field in its complete form. This enables quantitative observation of wave phenomena that help understand wave-particle interaction, which is an important process of energy transport in collision-less plasmas. The observation method using these sensors is unique and conventional. The element length of the electric field sensor is 5 m, which is appropriate for electrostatic waves with short wavelengths as well as electromagnetic waves. Electrostatic waves with short wavelengths of a few tens of meters are one of the critical targets in the FACTORS mission. The receiver consists of a low-frequency receiver (<100 Hz) that observes low-frequency waves such as Alfven waves and ElectroMagnetic Ion Cyclotron (EMIC) waves, a middle frequency receiver (<20 kHz) that covers ion cyclotron harmonics and whistler mode waves, and a high-frequency receiver (<10 MHz) that can monitor magnetospheric activity with electromagnetic waves for example, Auroral Kilometric Radiation (AKR). Combining a waveform acquisition-based receiver and on-board digital processing such as FFT produces output data as waveforms as burst observations and frequency spectra as over-view observations. On the other hand, by using six monopoles instead of the electric field sensors commonly used as 3-axis dipole sensors, an interferometry mode is implemented to calculate the wavefront, phase velocity, and wavelength of the wave by capturing the phase difference between the waves observed by different monopole sensors.

Based in the international collaboration, Sweden is set to provide the preamplifiers of electric field sensors and the low-frequency receiver.

7.2.5 Magnetic field measurement (DC-100Hz)

The magnetic field measurement in a frequency range less than 100 Hz has already been established with past satellite missions such as Arase and Mio, and meets the performance requirements of FACTORS.

7.2.6 Conjugate observations with ground-based network

The following is a summary of items to be compared and discussed regarding satellite observations and ground-based observations.

1. In the case of satellite scientific instrument observations, in-situ observation data on space and terrestrial magnetospheric plasma phenomena will be limited to what area and time in orbit? What is the temporal and spatial resolution?
2. For ground-based instruments using remote-sensing measurement methods, what is the area (latitude, local time, altitude, etc.) and time period (season, local time, etc.) of the observation target? What is the temporal and spatial resolution?

Currently, research institutes in Japan and around the world are auroral imaging network observations, magnetic field observations, ionospheric radar observations, etc., and are elucidating the dynamics of auroras and related phenomena through ground-based multi-point observations. Comparison of these ground-based observations with satellite observations of plasma particles and electromagnetic field/waves is difficult with respect to the part of the fine structure that FACTORS focuses on. Therefore, it is intrinsically important to realize simultaneous particle and auroral imaging observations by FACTORS.

On the other hand, since the area observed by FACTORS is limited to the satellite orbit, it will be combined with data from ground-based wide-area network observations to elucidate how phenomena on different scales are triggered and varied within the global-scale auroral activities. In other words, satellite observations can elucidate the fine spatio-temporal structure of the site, while ground-based observations can provide a three-dimensional understanding of the variations in the surrounding environment on a global scale. Thus, ground-based observations of the aurora and related phenomena and FACTORS observations are complementary from a global perspective, and it is highly significant for both to cooperate in their observations.

Besides such considerations, it is noteworthy to mention that Ground-based observations of the density and velocity of electrons/ions are possible using the new European Incoherent Scatter (EISCAT_3D) radar, which will provide 3-dimentional view of ionosphere and thermosphere. Collaborations with EISCAT_3D and IS radar are important to understand the cross-energy coupling by observing both inflow/outflow of energy and mass. In addition, ground auroral imager networks, magnetometer networks, SuperDARN radar networks, VLF wave networks, riometer networks operated by Japanese and international science groups provide comprehensive picture of precipitations of particles from the space and dynamics of the magnetosphere/ionosphere. Collaborations with these ground-based observations are also essential.

7.3 Major flight / ground trades

The major functional division of the satellite / ground system is described in terms of how to select the data necessary to achieve scientific objectives from the large amount of data acquired by the onboard instruments, and how to transmit the selected data to the ground.

As with NASA's MMS satellite, the observation data is acquired in continuous burst mode and survey mode (see Section 7.4.3) over a wide area of the polar regions, downlinked first to the survey mode data (i.e., low-resolution data), and then downlinked to the ground in order of priority, selecting only the time periods in which plasma phenomena such as ion acceleration are found based on the pre-downlinked survey mode data. The unselected portions are overwritten after a certain period of time.

It is possible to select observation data to be downlinked autonomously by using the onboard software, but this is a quite advanced approach and involves significant risk. Therefore, the design should allow data selection on the ground.

7.4 Data to be returned in the course of the investigation (= mission data): telemetry data, sample data etc. [2-2-1]

7.4.1 Overview of the scientific instruments

7.4.1.1 MGF (Fluxgate magnetometer)

MGF is a fluxgate magnetometer. It observes magnetic field vectors from DC to 100 Hz. The sensor of the MGF is mounted on the two-stage extendable MAST, which is 4m long.

7.4.1.2 EPWI (Electric field and Plasma Wave Investigation)

EPWI consists of two types of sensors and three types of receivers. The sensors are the tri-axial electric field sensor for electric fields and the search coil magnetometer for magnetic fields. The tri-axial search coil magnetometer is installed at the top of the extendable two-stage MAST, which is 4m long. For the receiver part, three receivers are installed depending on the frequency bands. The High-frequency receiver (HFR) covers the frequency range below 10 MHz, while the Middle-frequency receiver (MFR) is below 20 kHz. The MFR has the capability of the notable observation of so-called "interferometry" that can identify phase velocities of observed plasma waves by using the dipole sensor as two monopole sensors. The Low-frequency receiver (LFR) is dedicated to observing low-frequency waves below 100 Hz. The LFR also observes satellite potentials that lead to the identification of plasma densities and temperatures. The onboard digital processing applied to observed data provides the physical quantities such as frequency spectra and compressed waveform data.

7.4.1.3 LP (Langmuir probe)

The Langmuir probe is an instrument based on a well-established measurement technique, and it consists of a sensor and an electronic part. The sensor over swept voltages collects ions and electron currents, and the instrument outputs the relation of currents and voltages. The data derive plasma densities and electron temperatures.

7.4.1.4 LIMS (Low-energy ion energy-mass spectrometer)

LIMS detects ions with energies from 0.01 to 25 keV/q. Using a combination of an electrostatic energy-per-charge analyzer and a time-of-flight (TOF) velocity analyzer, LIMS provides ion fluxes, and then, ion velocity distribution functions, with energy and species discrimination. LIMS can also provide full pitch angle coverage, when satellite attitude is controlled as capturing the local geomagnetic field direction into the LIMS field-of-view, since LIMS has 360deg planar field-of-view.

7.4.1.5 SIMS (Supra-thermal ion energy-mass spectrometer)

SIMS detects ions with energies from <1 to 2000 eV/q. It provides ion fluxes and velocity distribution functions with energy and species discrimination by using techniques similar to LIMS. The energy range of SIMS covers background thermal ions coming from the ram direction of the satellite as they are measured with higher energies due to the satellite motion. SIMS can change pointing directions of its field-of-view electrically, to capture the ram direction.

7.4.1.6 SIMS-G (Supra-thermal ion energy-mass spectrometer for gyration phase capture)

SIMS-G is an identical instrument to SIMS. SIMS-G and SIMS are located with the orthogonal arrangement on the satellite to perform the simultaneous measurement of the pitch angle distribution and gyration phase distribution of ions.

7.4.1.7 LESA (Low-energy electron spectrum analyzer)

LESA is an electrostatic energy-per-charge analyzer for electron measurements. It provides energy spectra of electron fluxes with very high time resolution and full pitch-angle coverage.

7.4.1.8 HESA (High-energy electron spectrum analyzer)

HESA is an SSD-based electron detector. It provides energy spectra of high-energy electron fluxes.

7.4.1.9 VISAI (Visible auroral imager)

VISAI is a monochromatic imager. It observes the distribution of visible auroral emission intensity with the highest time and spatial resolutions which reflect the energy flux of precipitating electrons into the ionosphere.

7.4.1.10 FUVI (Far-ultraviolet imager)

FUVI is a monochromatic imager. It can operate even in the sunlit region and observe the distribution of far-ultraviolet auroral emission intensity with the moderate resolution which reflects the energy flux of precipitating electrons.

7.4.2 Telemetry strategy for scientific data

The mission defines the following observation mode, which depends on the observation region and target as shown in Section 10.1.

Survey mode

Long time low-resolution observation mode, in which event selection is performed on the ground after downlink to determine which period of data acquired in Burst mode and Burst-H mode should be downlinked.

Burst mode

A mode that performs detailed observations in bursts, in parallel with Survey mode observations, but downlinks are selectively performed based on the results of Survey observations.

Burst-H mode

High-resolution image acquisition mode. The observation period is selective, specified from the ground, and downlink availability is determined based on the results of the Survey mode observation.

7.4.3 Instrument performance requirement and measurement performance

Table 7.4.3-1 shows the relationship between requirements for the onboard scientific instruments and acquired data.

Table 7.4.3-1. Performance of onboard science instruments and requirements. Satellite means the satellite on which the instrument is installed; (A): FACTORS-A and (B): FACTORS-B.

Instrument (Satellite)	**Instrument performance requirement**	**Mode**	**measurement performance**	**Data rate [kbps] 30% compressed**
MGF (A, B)	RI-1, RI-2, RI-3, RI-4, RI-5, RI-6, RI-13, RI-14	survey	three axes, sampling 256 Hz	8
EPWI (A, B)	RI-1, RI-2, RI-3, RI-5, RI-7, RI-10, RI-11,RI-12, RI-14	survey	Electric field: Low-frequency receiver: <100 Hz, Spectra, Waveform Middle-frequency receiver: <20 kHz, Spectra High-frequency receiver: <10 MHz, Spectra Magnetic field: Middle-frequency receiver: <20 kHz, Spectra Satellite potential: 8points/sec	54
		burst	Electric field: Middle-frequency: <20 kHz, Waveform (3ch) Magnetic field: Middle-frequency: <20 kHz, Waveform(3ch)	1843
LP (A, B)	RI-7, RI-10	survey	Time resolution: 1/3 sec	14
LIMS (A, B)	RI-6	survey	Energy range: 0.01–25 keV/q Total FOV: 360deg × 5deg Angular resolution: 22.5deg × 5deg $M/\Delta M > 4$ Time resolution 0.1 s	170
		burst	same as above, but reporting each particle detection event (LIST data)	430
SIMS (A)	RI-13, RI-14	survey	Energy range: <1–2000 eV/q Total FOV: 360deg × 80deg Angular resolution: 22.5deg × 10deg $M/\Delta M > 4$ Time resolution 0.5 s	220
		burst	same as above, but reporting each particle	430

			detection event (LIST data)	
SIMS-G (A)	RI-13, RI-14	survey	Energy range: <1–2000 eV/q Total FOV: 360deg × 80deg Angular resolution: 22.5deg × 10deg $M/\Delta M > 4$ Time resolution 0.5 s	220
		burst	same as above, but reporting each particle detection event (LIST data)	430
LESA (A, B)	RI-4	survey	Energy range: 0.01–30keV Total FOV: 360deg × 4.5deg Angular resolution: 5.625deg × 4.5deg Time resolution 0.022 s	220
HESA (B)	RI-5	survey	Energy range: <100–2000 keV Angular resolution: 10deg × 10deg Time resolution: 0.05 s	5
		burst	same as above, but reporting each particle detection event (LIST data)	70
VISAI (B)	RI-8	survey	Wavelength: 670 nm (N2 aurora) Spatial resolution: 2 km × 2 km (at apogee) Coverage area: 500 km × 500 km (at apogee) Time resolution: 1 s	310
		burst	Same as above, but spatial resolution is 1 km × 1 km (at apogee), and time resolution is 0.1 s (10 fps).	1200
		burst-H	Same as above, but spatial resolution is 0.5 km × 0.5 km (at apogee), and time resolution is 0.05 s (20 fps).	9600
FUVI (A)	RI-9	survey	Wavelength: 135 nm (Oxygen aurora) Spatial resolution: 2 km × 2 km (at apogee) Coverage area: 500 km × 500 km (at apogee) Time resolution: 1 s	310
		burst	Same as above, but spatial resolution is 1 km × 1 km (at apogee), and time resolution is 0.2 s (5 fps).	600
		burst-H	Same as above, but spatial resolution is 1 km × 1 km (at apogee), and time resolution is 0.1 s (10 fps).	6000

7.5 Science data management and science center.

The data management plan of the FACTORS mission will be prepared, which includes data processing, data quality control, and data archiving and distribution. The science data of FACTORS will be distributed to researchers and the public with the standard file format. The integrated data analysis software to analyze the FACTORS data and related satellites/ground-based/simulation data will also be developed. NASA/CDF (Common Data Format) and SPEDAS (Space Physics Environment Data Analysis System) that are a de facto standard data format and analysis software respectively in the international heliophysics science community are a plausible data file format and software for the analysis. They are essential to realize the integrated data analysis using FACTORS and other satellite/ground-based data.

Currently, ISAS/JAXA and ISEE/Nagoya University have operated the center for heliospheric science (CHS), and the data of Arase and related ground-based/simulation are archived and opened to the public via the CHS webpage. The CHS has also developed the data analysis software that is a plug-in of SPEDAS, and contributed for planning of the coordinated observations with ground-based and other satellite missions, which have been important to gain the science achievements through the integrated analysis. Since such activities would be essential for relevant scientists, we explore the capability of similar activities at the CHS in consultation with JAXA and ISEE/Nagoya University.

8 Scientific traceability matrix (draft) [1-4-1]

The traceability from science goals to instrument functional and performance on board the FACTORS satellites are shown in **Table 8-1**. Details of RS (Science requirements) and RI (Instrument requirement) are shown in **Table 6-1** and **6-2** respectively, and **Table 7.4.3-1** shows relationship between RI and each instrument.

Table 8-1. Traceability from science goals to instrument functional and performance on board the FACTORS satellites.

Science requrements (RS) / Mission Goals and Objectives		RS-1 (Plasma wave)	RS-2 (High frequency wave)	RS-3 (Field aligned current)	RS-4 (Poynting flux)
Mission Goal-1: Understanding inflow process	A: Cross-scale energy and material couplings between the magnetosphere-ionosphere	✔	✔	✔	✔
	B: Field-aligned acceleration of plasmas to drive the couplings	✔		✔	
	C: Generation of energetic electron precipitations and its relationship to the couplings	✔			
Mission Goal-2: Understanding outflow process	A: Characteristics of plasma waves with long wavelengths associated with accelerated ions	✔	✔		✔
	B: Characteristics of plasma waves with short wavelengths associated with accelerated ions	✔	✔		✔
Instrument peformance requirements (RI)		(RI-1) Observation of six components of electric and magnetic field waveforms in the frequency range of ULF to VLF using electric field sensors, search coil magnetometers and fluxgate magnetometers on two satellites.	(RI-2) Observation of electric field spectra in the HF frequency range using an electric field sensor. The target waves are AKRs and UHR waves.	(RI-3) Observation of magnetic field waveforms in the frequency range of ULF to 256 Hz using a fluxgate magnetometer.	(RI-1) Observation of six components of electric and magnetic field waveforms in the frequency range of ULF to VLF.
FACTORS Instruments					
MGF (Fluxgate magnetometer)	three axes, DC-100 Hz	✔	✔	✔	✔
EPWI (Electric field and plasma wave investigation)	three axes, <10 MHz (electric field) search coil, <20 kHz (magnetic field)	✔	✔		✔
LP (Langumir probe)	time resolution: 1/3 sec				
LIMS (Low-energy ion energy-mass spectrometer)	0.01-25 keV/q ions, species discrimination				
SIMS (Supra-thermal ion energy-mass spectrometer)	<2 keV/q ions, species discrimination				
SIMS-G (Supra-thermal ion energy-mass spectrometer for gyration phase capture)	<2 keV/q ions, species discrimination				
LESA (Low-energy electron spectrum analyzer)	0.01-30 keV electron				
HESA (High-energy electron spectrum analyzer)	<100-2000 keV electron				
VISAI (Visible auroral imager)	670 nm/FOV: 500×500 km/Res: 2×2 km				
FUVI (Far-ultraviole imager)	135 nm/FOV: 500×500 km/Res: 2×2 km				

Science requrements (RS) / Mission Goals and Objectives		RS-5 (Electron flux)	RS-6 (High-energy electron flux)	RS-7 (Low-energy ion)	RS-8 (Electron density)
Mission Goal-1: Understanding inflow process	A: Cross-scale energy and material couplings between the magnetosphere-ionosphere	✔		✔	✔
	B: Field-aligned acceleration of plasmas to drive the couplings	✔		✔	✔
	C: Generation of energetic electron precipitations and its relationship to the couplings	✔	✔	✔	✔
Mission Goal-2: Understanding outflow process	A: Characteristics of plasma waves with long wavelengths associatied with acceleratied ions	✔		✔	✔
	B: Characteristics of plasma waves with short wavelengths associatied with acceleratied ions	✔		✔	✔
Instrument peformance requirements (RI)		(RI-4) Observation of electron flux and pitch angle distribution in the energy range from 10 eV/q to 30 keV/q with a time resolution less than 20 msec using an energy analyzer.	(RI-5)Observation of precipitating electron flux in the energy range from 10 keV to 1 MeV with temporal resolution about a few tens msec using a semiconductor detector.	(RI-6) Observation of ion flux and pitch angle distribution in the energy range from ~1 eV/q to 25 keV/q using energy-mass spectrometers.	(RI-7) High frequency electric field observation using electric field sensors or observation by a Langmuir probe.
			(RI-11) Observation of electric field waveform that covers the VLF frequency range (<20 kHz) using electric field sensors.	(RI-13) Observation of heavy ions from the ram direction by ion energy-mass spectrometers with deflectors.	(RI-2) Observation of electric field spectra in the HF frequency range using an electric field sensor.
FACTORS Instruments					
MGF (Fluxgate magnetometer)	three axes, DC-100 Hz	✔	✔	✔	
EPWI (Electric field and plasma wave investigation)	three axes, <10 MHz (electric field) search coil, <20 kHz (magnetic field)		✔		✔
LP (Langumir probe)	time resolution: 1/3 sec				✔
LIMS (Low-energy ion energy-mass spectrometer)	0.01-25 keV/q ions, species discrimination			✔	
SIMS (Supra-thermal ion energy-mass spectrometer)	<2 keV/q ions, species discrimination			✔	
SIMS-G (Supra-thermal ion energy-mass spectrometer for gyration phase capture)	<2 keV/q ions, species discrimination			✔	
LESA (Low-energy electron spectrum analyzer)	0.01-30 keV electron	✔			
HESA (High-energy electron spectrum analyzer)	<100-2000 keV electron		✔		
VISAI (Visible auroral imager)	670 nm/FOV: 500×500 km/Res: 2×2 km				
FUVI (Far-ultraviole imager)	135 nm/FOV: 500×500 km/Res: 2×2 km				

Science requrements (RS) / Mission Goals and Objectives		RS-9 (Auroral image)	RS-10 (Satellite potential)	RS-11 (Wavelength measurements (short))	RS-12 (Synchronized measurements of ion and waves)
Mission Goal-1: Understanding inflow process	**A: Cross-scale energy and material couplings between the magnetosphere-ionosphere**	✔			
	B: Field-aligned acceleration of plasmas to drive the couplings	✔	✔		
	C: Generation of energetic electron precipitations and its relationship to the couplings	✔	✔		
Mission Goal-2: Understanding outflow process	**A: Characteristics of plasma waves with long wavelengths associated with accelerated ions**		✔		✔
	B: Characteristics of plasma waves with short wavelengths associated with accelerated ions		✔	✔	✔
Instrument peformance requirements (RI)		**(RI-8) Visible aurora observation with following requirements: Field of view: ~500 km × 500 km at 4000 km altitude, Wavelength: N2 1PG (~670 nm), Spatial resolution: ~ 1 km × 1 km, Temporal resolution: a few Hz**	**(RI-10) Observation of electric field in the low frequency range or observation by a Langmuir probe with a time resolution less than 500 msec.**	**(RI-12) RI-12 Interferometric observations of electric fields with electric field monopole observations with tri-axial relatively short electric field sensors.**	**(RI-14) Species discriminated ion data production focusing on the selected directions, which should have time tags with accuracy better than ~100 μsec relative to time tags of the waveform data of plasma waves.**
		(RI-9) FUV aurora observation with following requirements: Field of view: ~500–1000 km × 500–1000 km at 4000 km altitude, Wavelength: 130–180 nm, Spatial resolution: less than ~ 5 km × 5 km, Temporal resolution: a few Hz			
FACTORS Instruments					
MGF (Fluxgate magnetometer)	three axes, DC-100 Hz				✔
EPWI (Electric field and plasma wave investigation)	three axes, <10 MHz (electric field) search coil, <20 kHz (magnetic field)		✔	✔	✔
LP (Langumir probe)	time resolution: 1/3 sec		✔		
LIMS (Low-energy ion energy-mass spectrometer)	0.01-25 keV/q ions, species discrimination				
SIMS (Supra-thermal ion energy-mass spectrometer)	<2 keV/q ions, species discrimination				✔
SIMS-G (Supra-thermal ion energy-mass spectrometer for gyration phase capture)	<2 keV/q ions, species discrimination				✔
LESA (Low-energy electron spectrum analyzer)	0.01-30 keV electron				
HESA (High-energy electron spectrum analyzer)	<100-2000 keV electron				
VISAI (Visible auroral imager)	670 nm/FOV: 500×500 km/Res: 2×2 km	✔			
FUVI (Far-ultraviole imager)	135 nm/FOV: 500×500 km/Res: 2×2 km	✔			