In-situ Observation Plans in Next Japanese Space Exploration Mission(FACTORS) for Ion Acceleration/Heating Processes in the Terrestrial Magnetosphere-Ionosphere Coupling System

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5: Swedish Institute of Space Physics, Sweden

The FACTORS mission

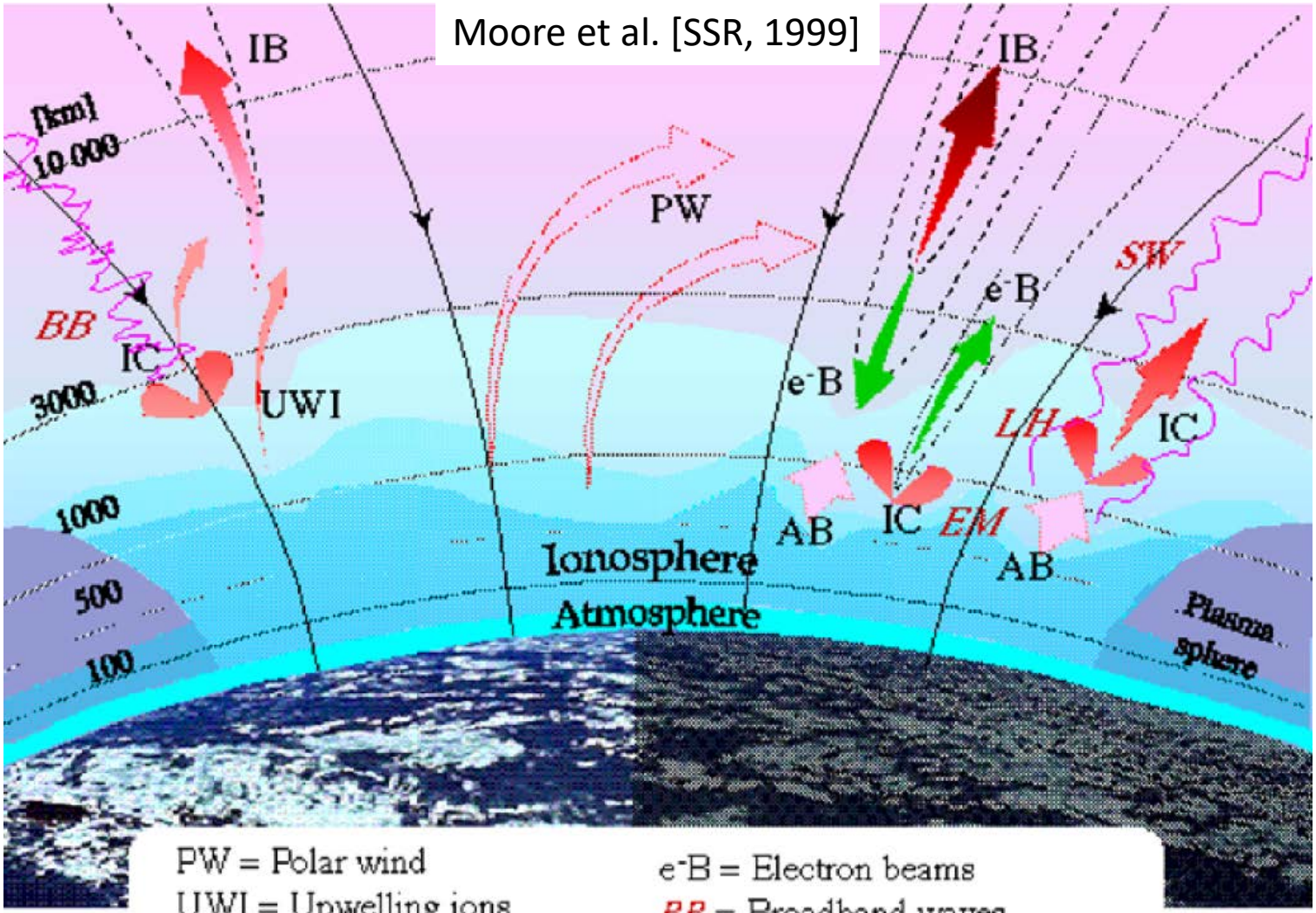
- First Japanese space physics mission using multiple(formation flight) compact(150-200 kg) satellite technologies for elucidating the magnetosphere-ionosphere-thermosphere(space-Earth) coupling processes/mechanisms
- Next Japanese community(flagship-type) mission in a sun-synchronous elliptical orbit with high-time/spatial resolutions based on our expertise obtained through Geotail, INDEX(Reimei), ERG(Arase), BepiColombo-MMO, and etc. after the success of ERG(Arase)

Outline of Today's Talk

1. Science background and subjects of FACTORS
   - Space-Earth coupling system applied to the universal space-planet coupling system
     - e.g., terrestrial ion outflows, plasma espace of unmagnetized planets, and also atmospheric erosion from exoplanets like hot Jupiter, super Earth
   - Examples of the INDEX observations
   - Missions for terrestrial plasma escape and regional coupling processes under development, approved, proposed
2. Mission concept and strategies of FACTORS
   - Integrated science observations initiated by ERG and new instruments
     - Wave-particle interaction analysis(WPIA) based on waveform measurements and velocity vector information of each particle detected, applied to ERG for the first time
     - New types of plasma/neutral particle instruments under development
   - Triangle-type research system
     - Established in the Japanese community first for ERG
   - Instrumental heritages and development plans
     - Previous/on-going satellite missions and SS-520-3 sounding rocket
   - International collaborations
     - Innosat by SNSB and OHB, F-mission by ESA

A Variety of Plasma Dynamics in the Terrestrial Polar Ionosphere

Moore et al. [SSR, 1999]



INDEX(Reimei, 2005)

The Reimei Satellite

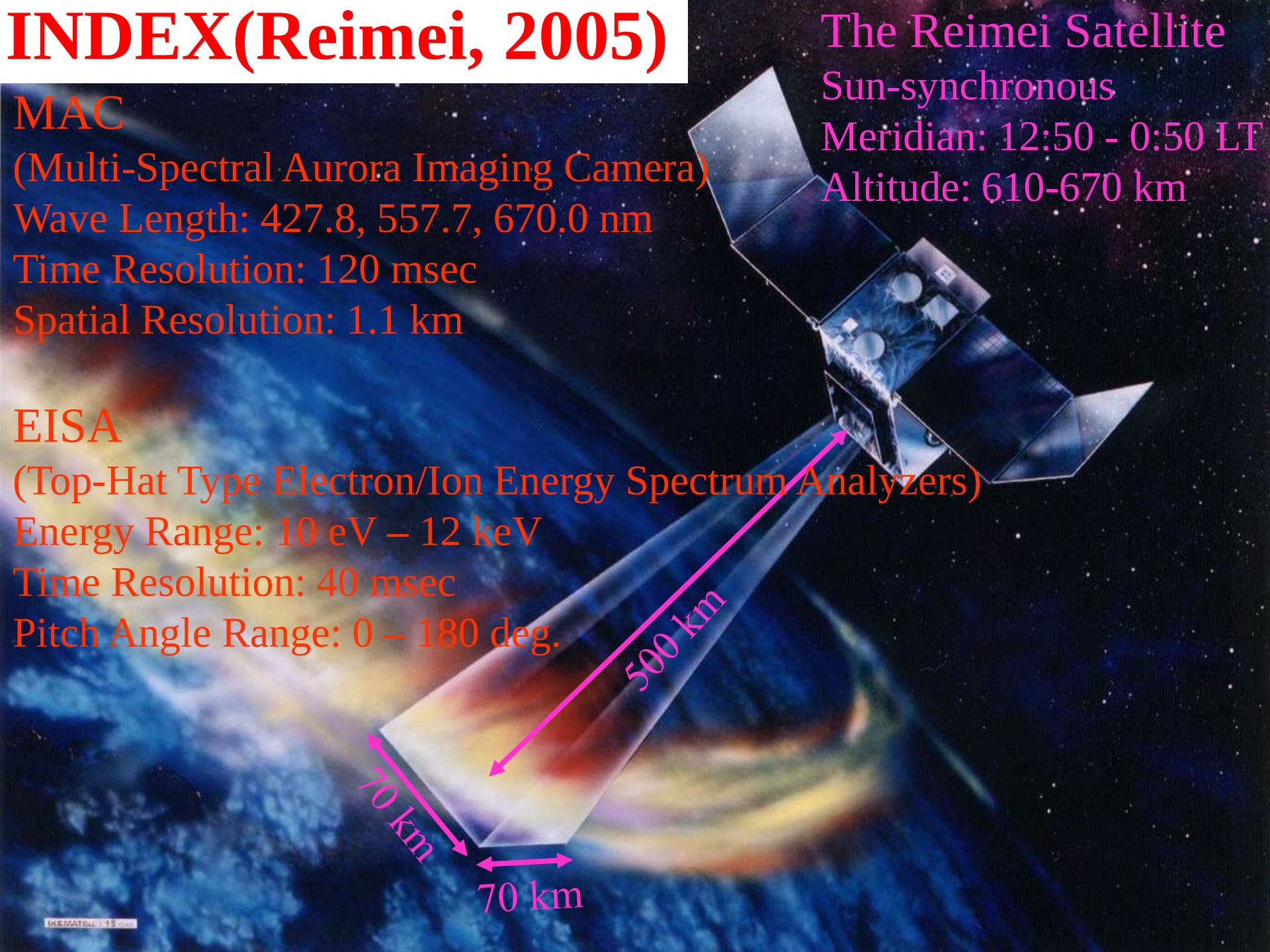
Sun-synchronous
Meridian: 12:50 - 0:50 LT
Altitude: 610-670 km

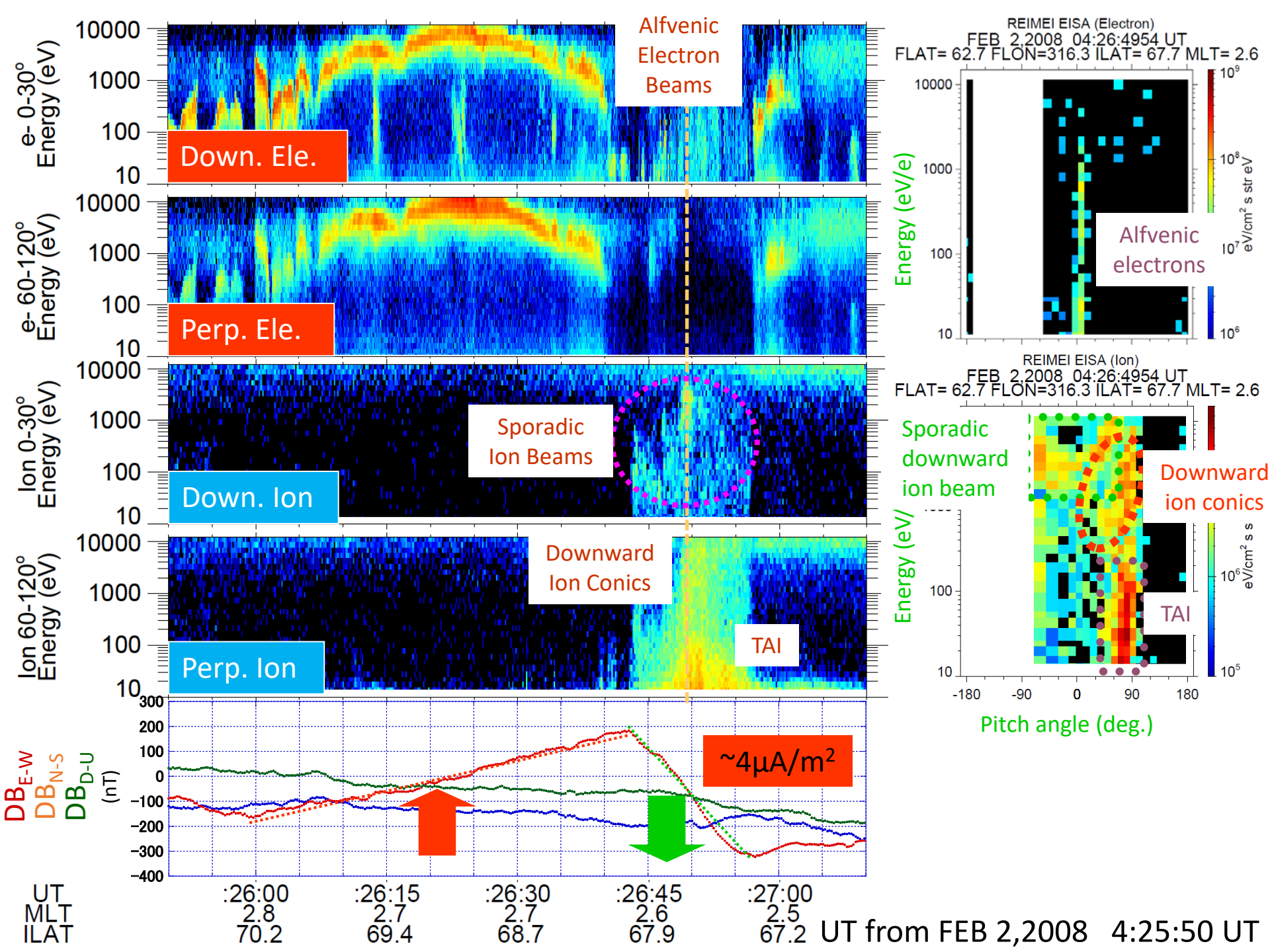
MAC

(Multi-Spectral Aurora Imaging Camera)
Wave Length: 427.8, 557.7, 670.0 nm
Time Resolution: 120 msec
Spatial Resolution: 1.1 km

EISA

(Top-Hat Type Electron/Ion Energy Spectrum Analyzers)
Energy Range: 10 eV – 12 keV
Time Resolution: 40 msec
Pitch Angle Range: 0 – 180 deg.




Alfvenic Electron Beams
Down. Ele.
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Sporadic Ion Beams
Down. Ion
Downward Ion Conics
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TAI
e- 0-30° Energy (eV)
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Sporadic downward ion beam
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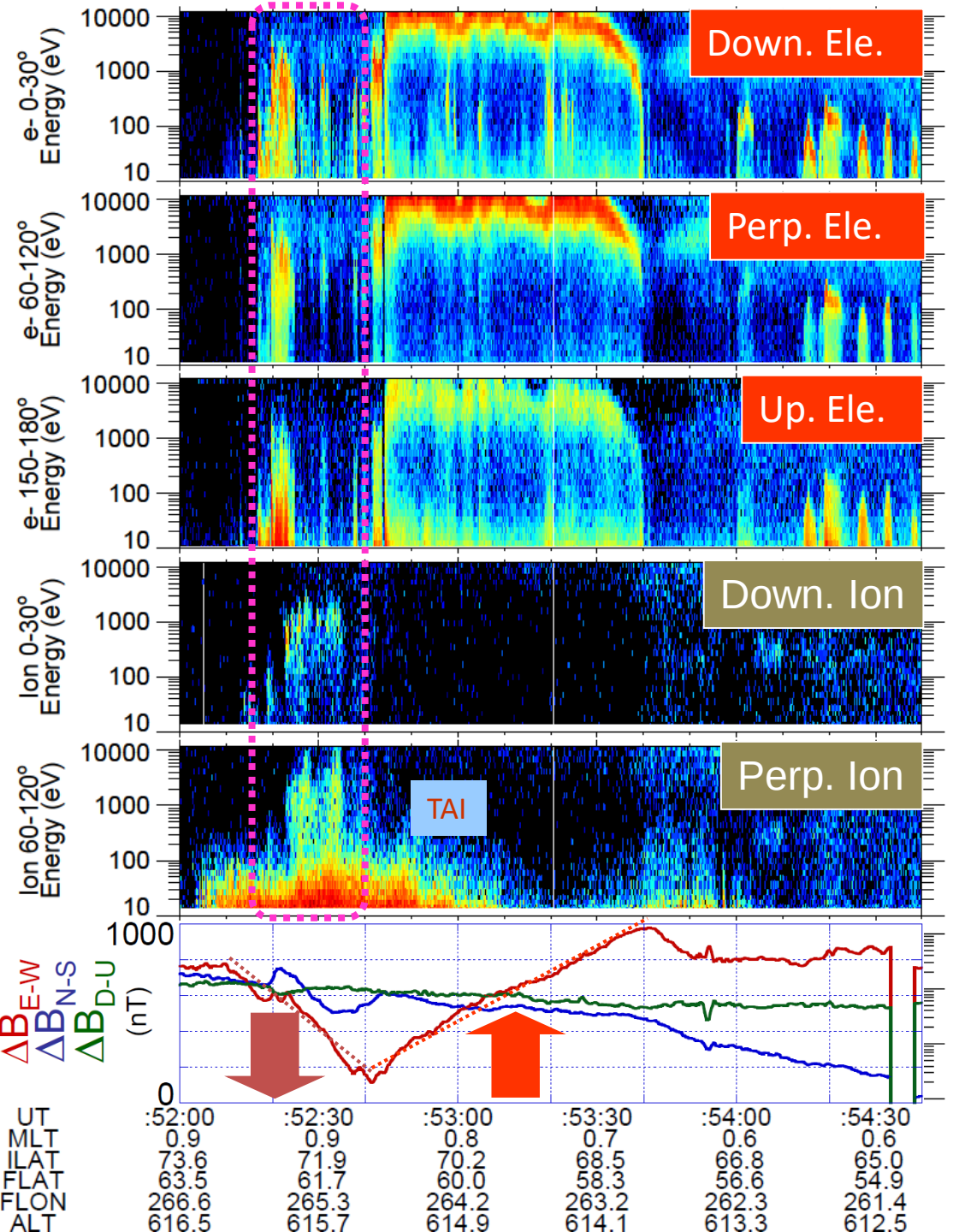
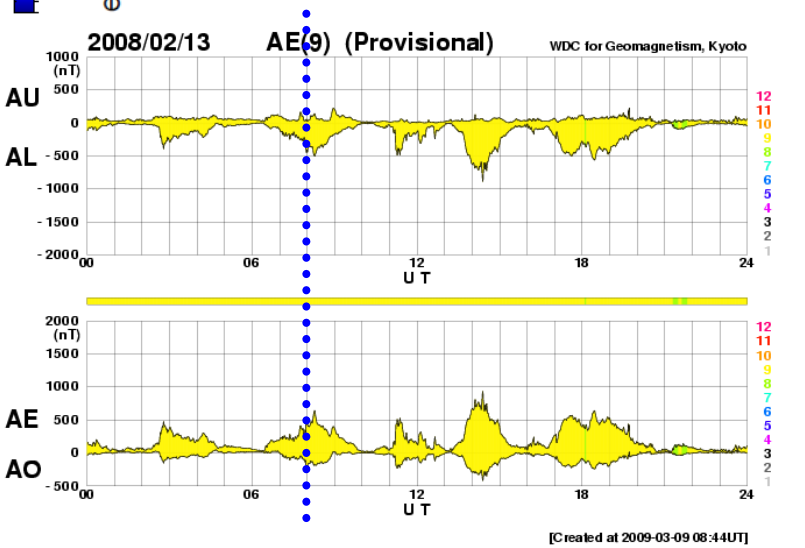


Auroral poleward expansion after an onset following the rapidly changing ray-type auroras at higher-latitudes

A similar event reported by Chaston et al. [2008] based on the simultaneous observations of auroral particles and emissions

Many sporadic ion beams emerging with TAIs between discrete electron signatures



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Research Objectives and On-going/Approved Mission Situation in Space Plasma Physics

- Terrestrial Magnetosphere and Ionosphere
  - Radiation belt/Geospace
    - VAP(NASA), ERG/Arase(JAXA), DSX(USA)
  - Magnetotail
    - Geotail(JAXA), CLUSTER II(ESA), THEMIS(NASA), MMS(NASA)
  - Shock/magnetopause
    - Geotail(JAXA), MMS(NASA)
  - Polar/auroral magnetosphere
    - DMSP(USA), CLUSTER II(ESA), CASSIOPE-ePOP(Canada)
- Planetary Magnetosphere
  - Hisaki(JAXA), JUNO(NASA), BepiColombo-MMO(ESA-JAXA), JUICE(ESA)
- Upper Atmosphere of Unmagnetized Planet
  - MAVEN(NASA)
- Solar Corona/Wind
  - Solar Orbiter(ESA), Parker Solar Probe(NASA)
- Exoplanetary Atmosphere
  - TESS(NASA), WSO-UV(Russia), JWST(NASA)

'Recent' flagship/full-size missions in space or under development

FACTORS

With MIT, MEME-X, CONNEX, F-Mission?

Overseas Space Mission Direction – NASA

Mechanisms of Energetic Mass Ejection-Explorer(MEME-X) as a next SMEX candidate

350 km × 1200 km elliptical orbits at ~85° inclination

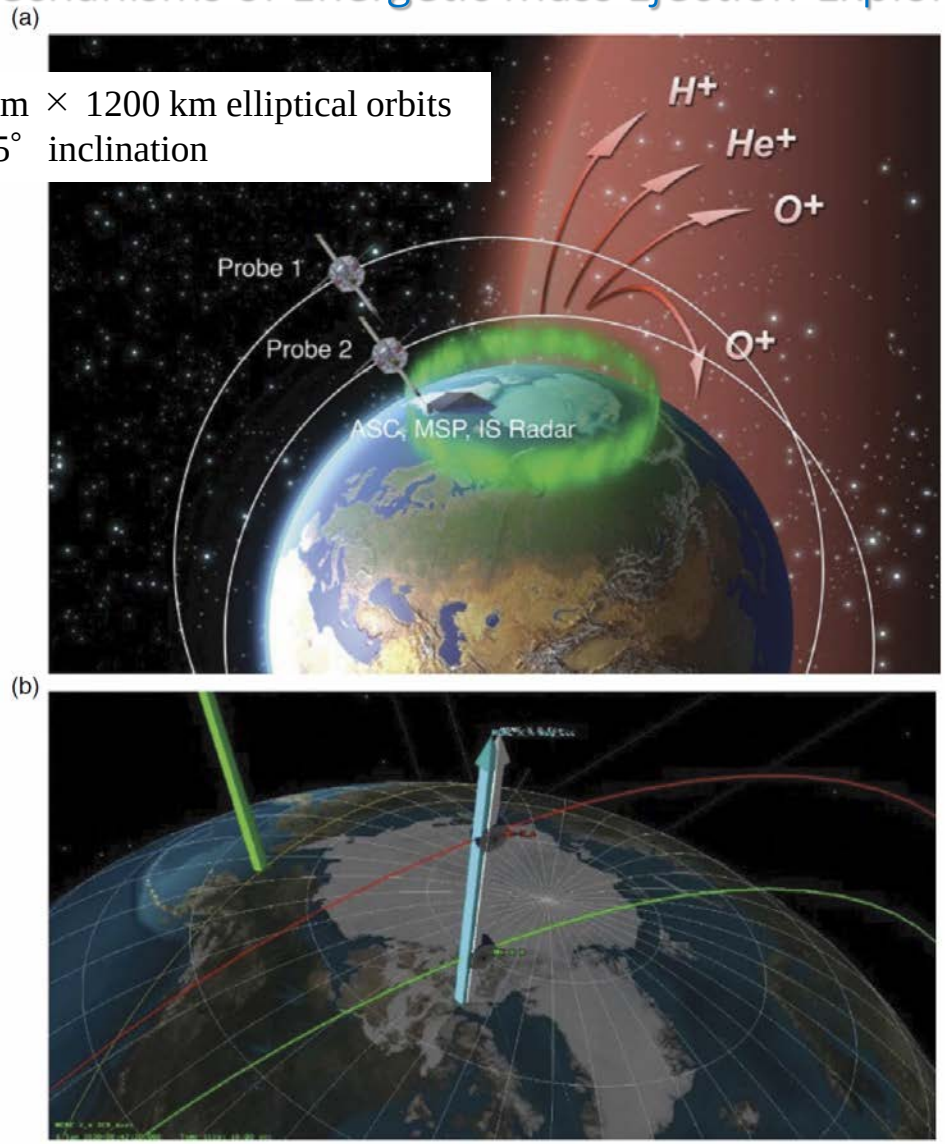
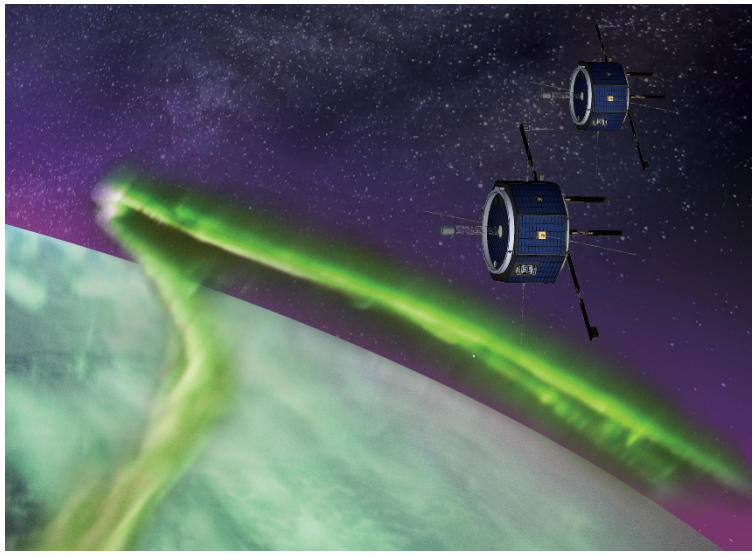


Figure 28.8 (a) Orbit concept for a mission point design to study AIM coupling using two orbiting probes, one or more ISR stations, and the Canadian GeoSpace Monitoring network. (b) Closeup of simulated orbits illustrating the moment when the two spacecraft are magnetically conjugate over the auroral oval in one hemisphere. Half an orbit later, they reverse positions vertically in the opposite hemisphere.



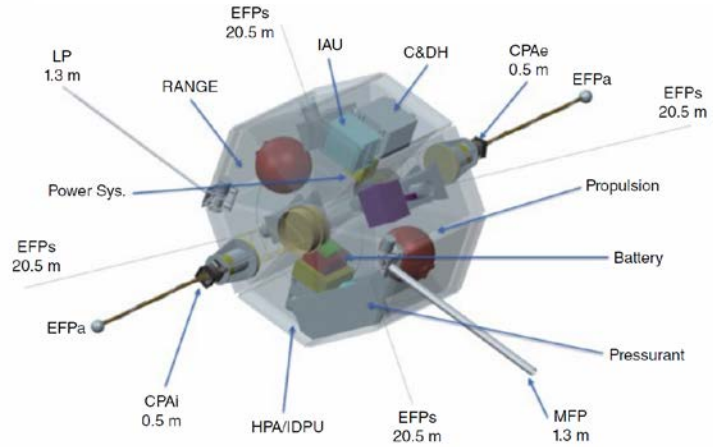
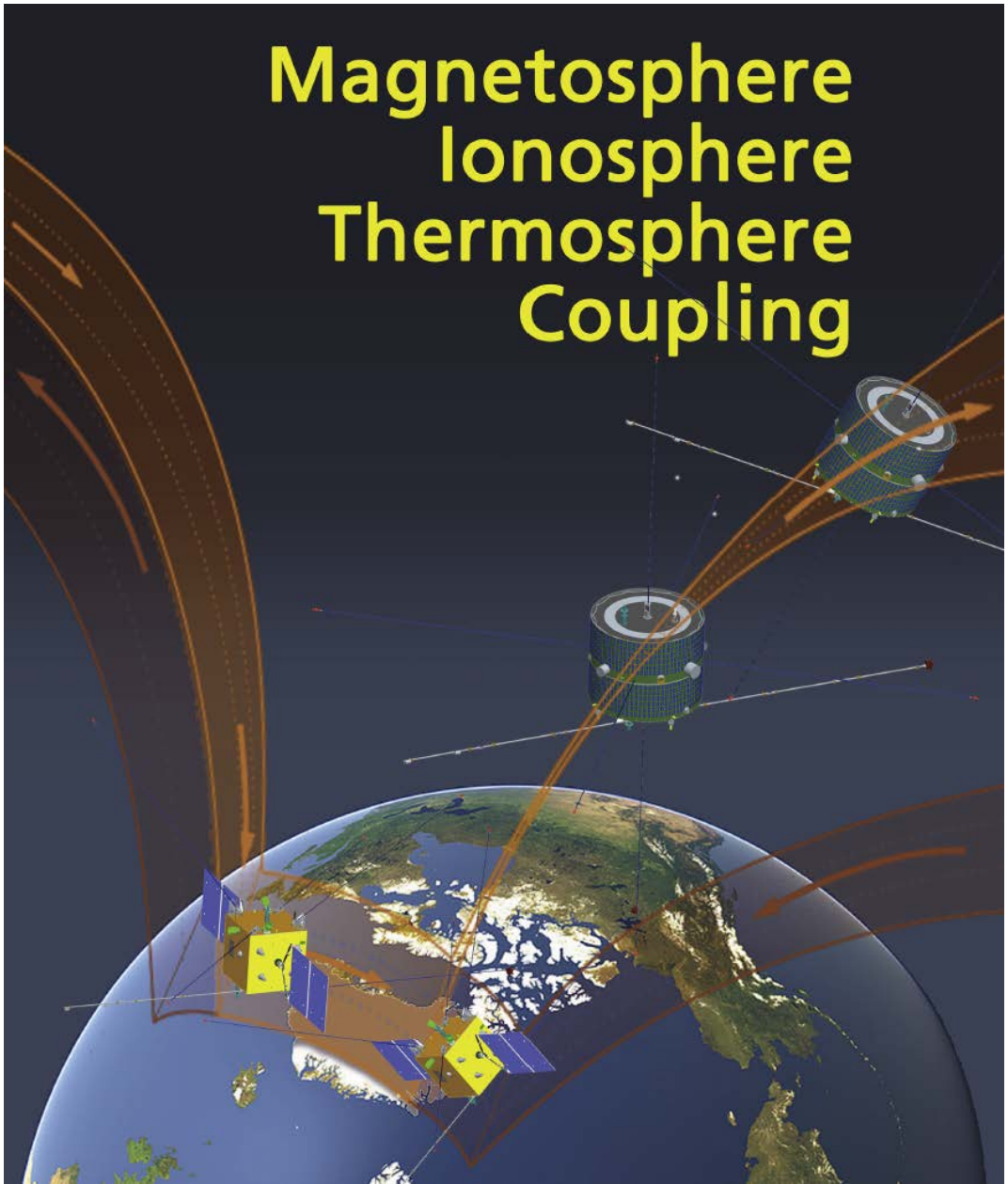


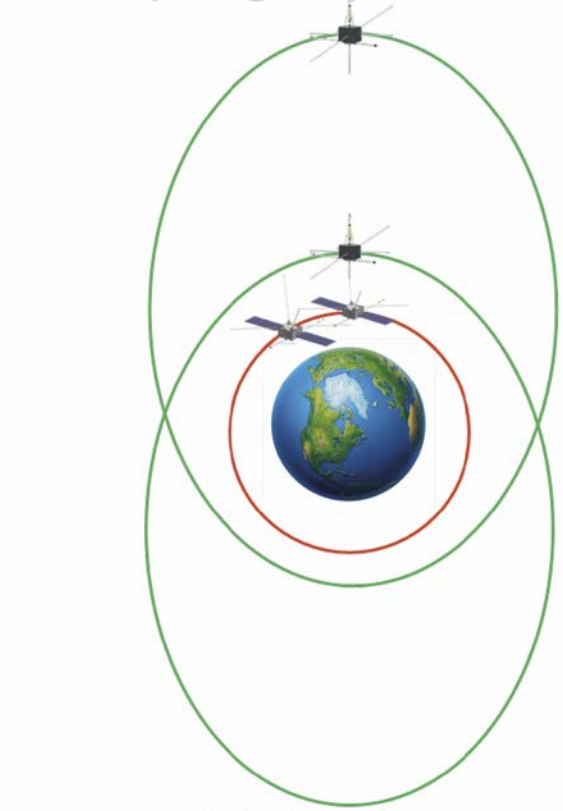
Figure 28.10 A spacecraft point design based on the THEMIS spacecraft bus for a small, efficient probe suitable for atmosphere-ionosphere-magnetosphere coupling studies described herein. EFP, MFP, LP, CPA (core plasma analyzer, e, i), HPA, RANGE (gas pressure).

Moore et al. [GM, 222, 2017]

Overseas Space Mission Direction – CAS

Magnetosphere-Ionosphere-Thermosphere Coupling Exploration(MIT)





Satellite	Ionosphere/ Thermosphere Satellite-A （ITA）	Ionosphere/ Thermosphere Satellite-B （ITB）	Magnetosphere Satellite-A （MA）	Magnetosphere Satellite-B （MB）
Inclination	90°	90°	90°	90°
Perigee Altitude	500 km	500 km	1 Re	1 Re
Apogee Altitude	1500 km	1500 km	7 Re	7 Re

Fig 7. The Orbits of the four spacecraft of the MIT Constellation mission.

ERG (Exploration of Energization and Radiation in Geospace)

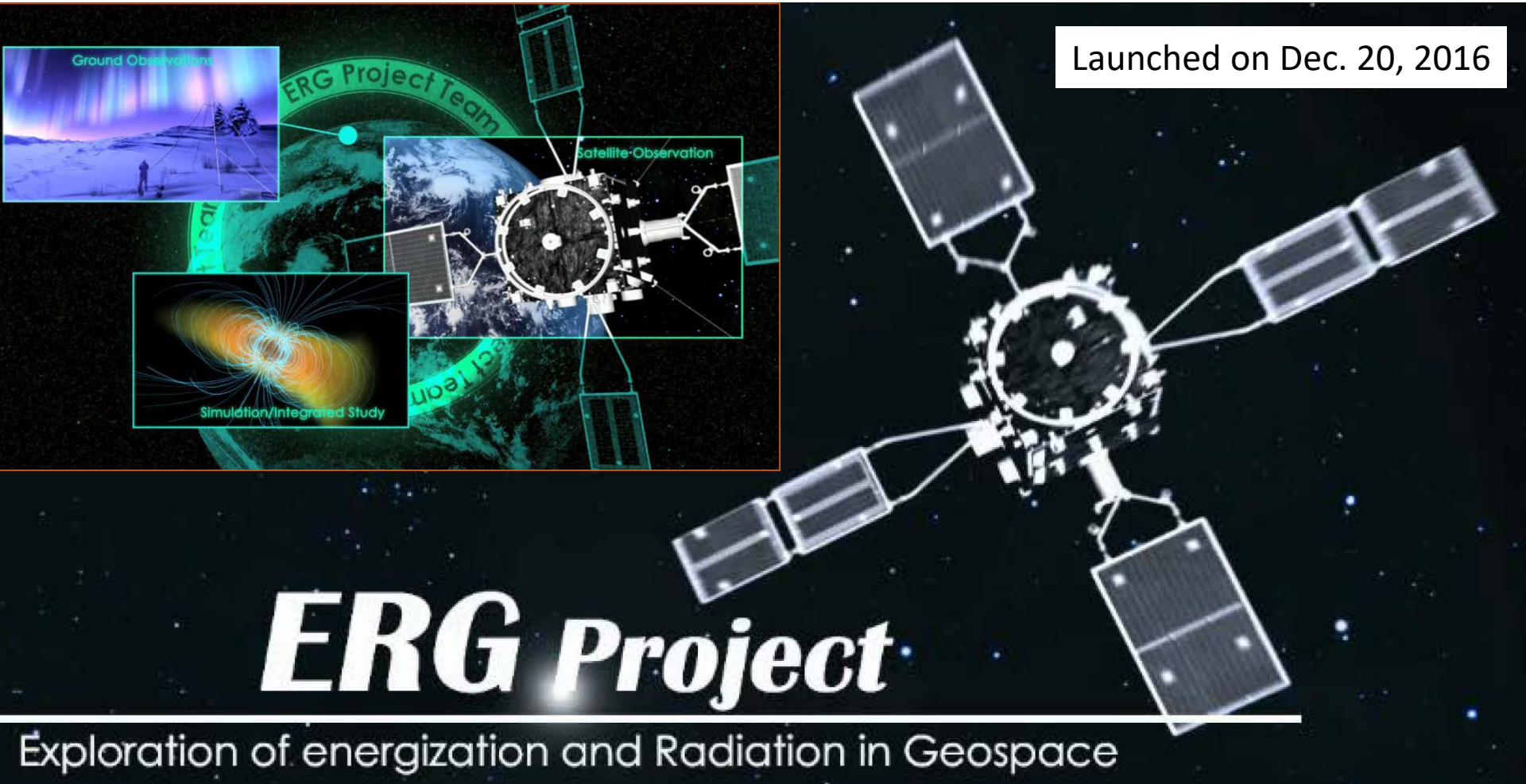
Dynamics of the radiation belt particles due to the cross-energy couplings

Acceleration, Transport, and Loss Processes of the Relativistic Particles

--- Radiation Belt (Wave-Particle-Field Coupling)

Conditions for the Acceleration, Transport, and Loss Processes

--- Space Storm (Cross-Energy/Sphere Coupling)



Breakthrough driven by the WPIA

In wave-particle interactions, the phase relation of waveforms and particle velocity vectors determines the energy flow direction.

$$\frac{d}{dt}\left(\frac{1}{2}mV^2\right) = \boldsymbol{E}\bullet\boldsymbol{V} = q\left|\boldsymbol{E}\right|\left|\boldsymbol{V}\right|\cos\theta$$

Energy flow balance

Particle ⇨ Waves

Waves ⇨ Particle

We need the time resolution enough to detect the above phase relation.

Plasma waves: **We succeeded the waveform capture in Geotail**

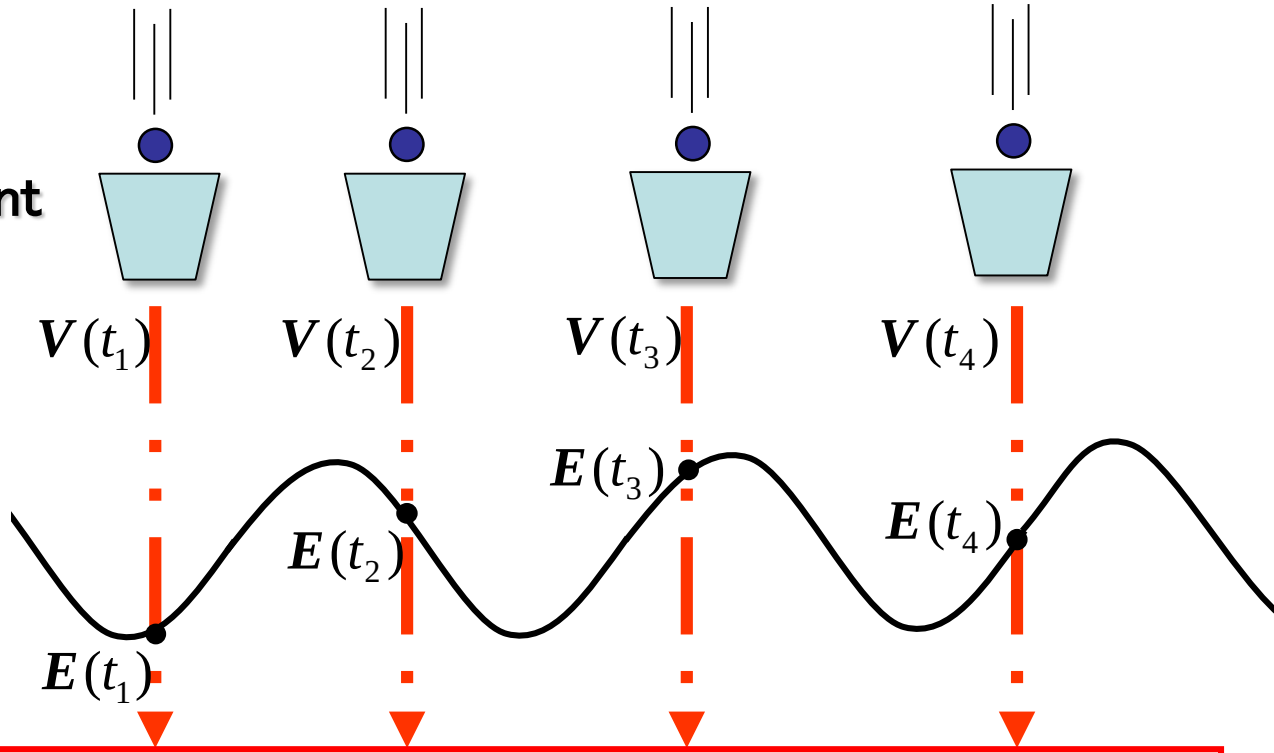
Particle: **Particle pulse detection with a few micro sec. accuracy has been achieved in the ERG mission.**

⇨ New attempt for identifying the phase relation of waves and particles

New measurement method – WPIA

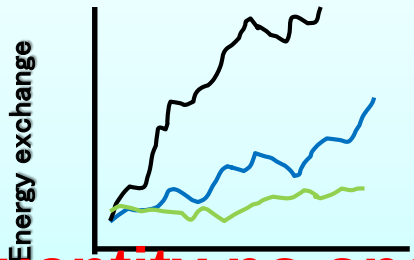
Plasma/particle instrument
(Particle measurement)

Plasma wave receiver
(Waveform measurement)



Record of the instantaneous wave vectors and velocity vector of each particle

Possible direct measurement of energy transfer

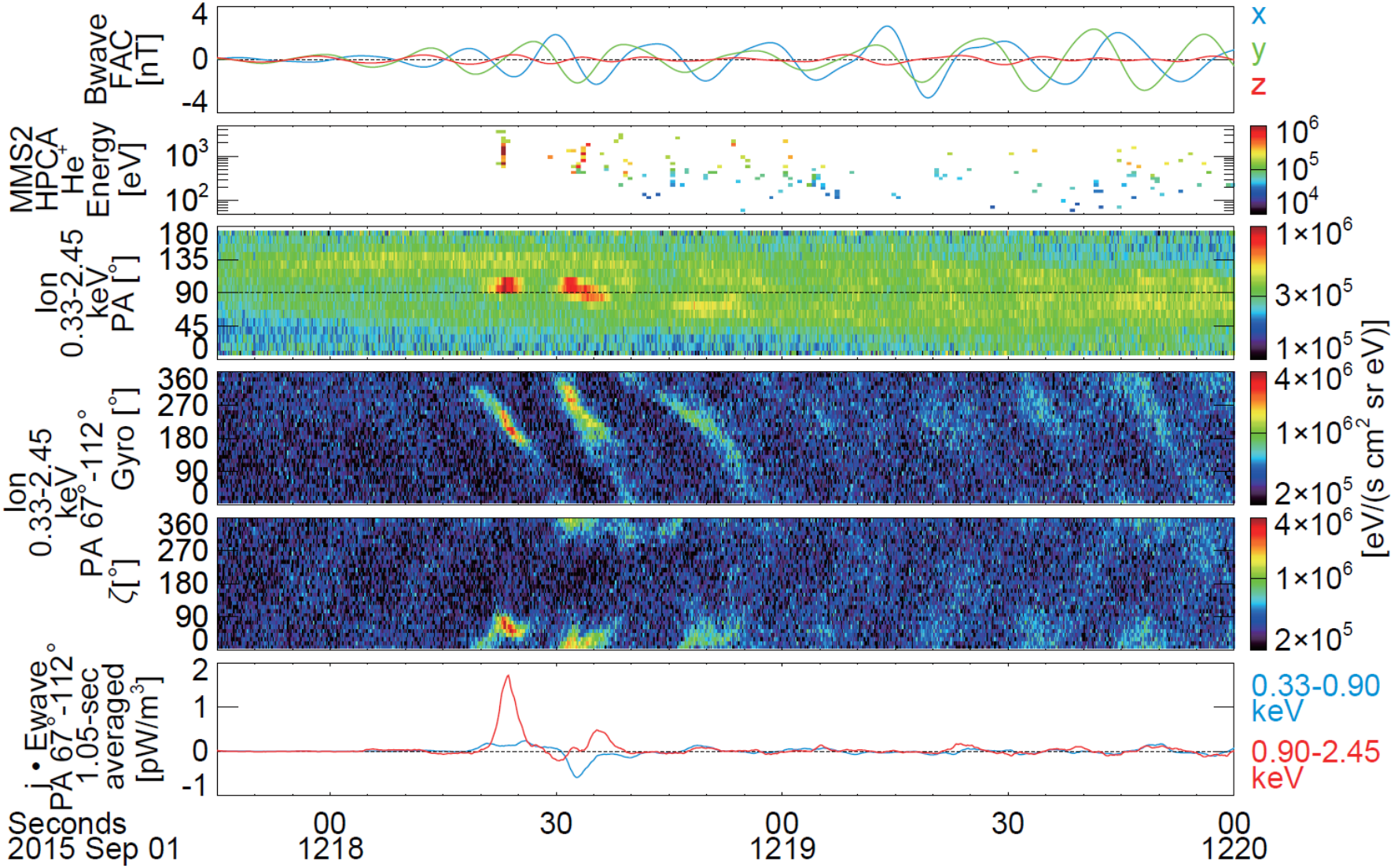


$$\frac{d}{dt}\left(\frac{1}{2}mV^2\right) = q\boldsymbol{E}(t)\bullet\boldsymbol{V}(t)$$

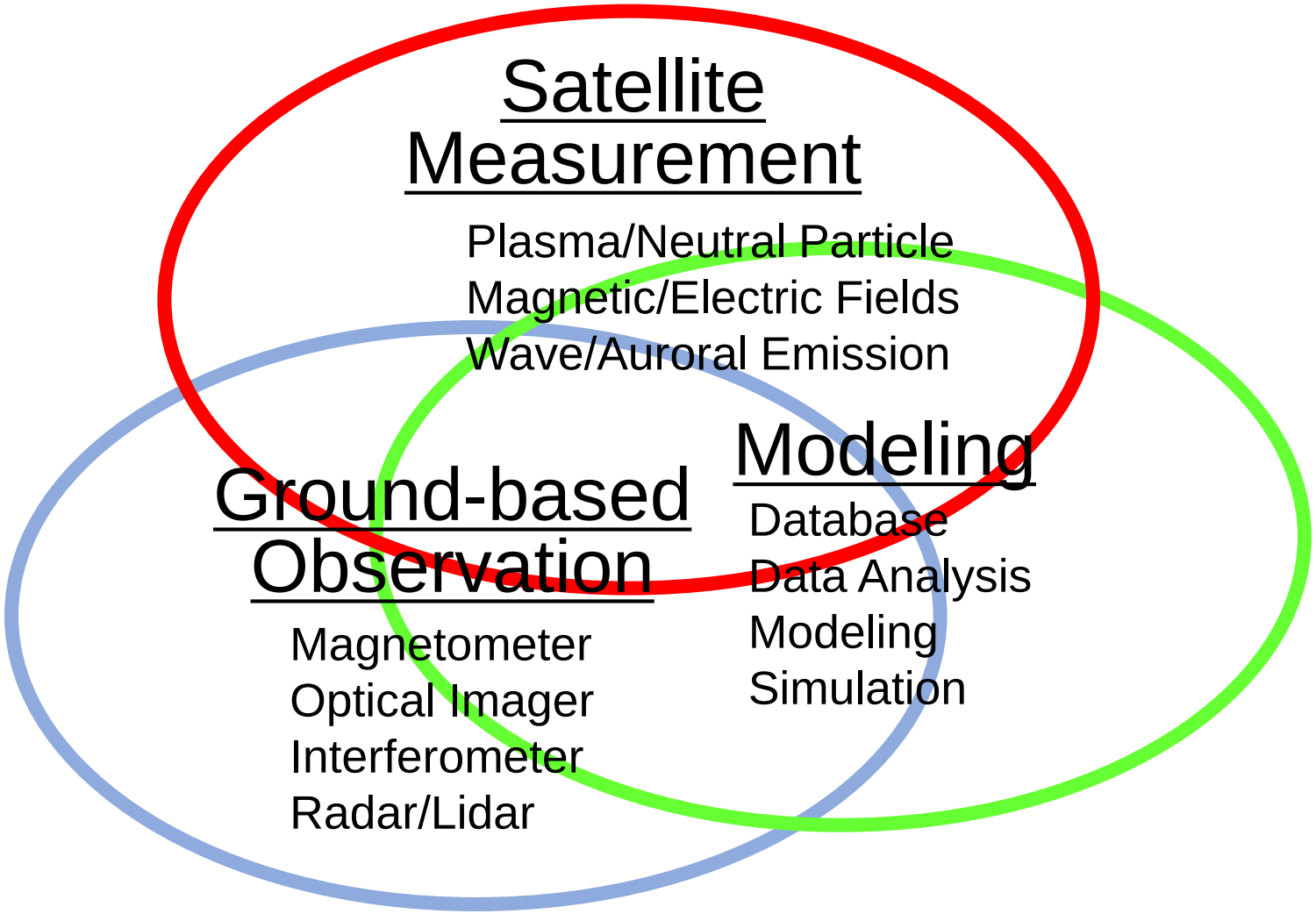
Physical quantity no one has seen before in space

An Example of Wave-Particle Interaction Analyses for Ions by Using the FPI/MMS Data

From the results by Kitamura et al. [Science, under review]



Triangle-type Research Framework by Satellite/Ground-Based Observations and Data Analysis/Modeling/Simulation



FACTORS

Frontiers of Formation, Acceleration, Coupling, and Transport Mechanisms Observed by the Outer Space Research System

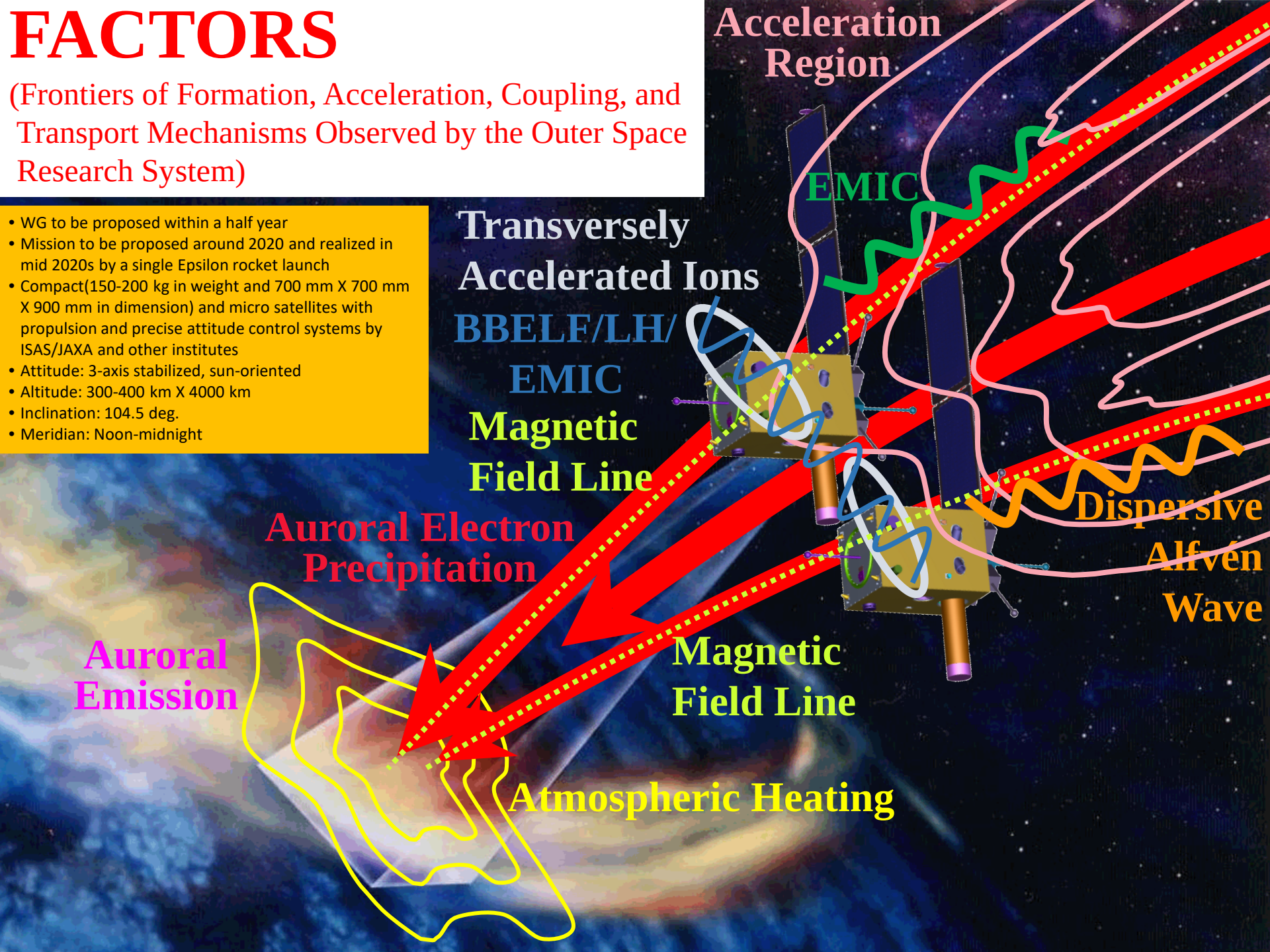
Overview and Strategy of FACTORS

- Next community/flagship-type mission in the Japanese space physics community after the ERG(Arase) mission
- Improvements/enhancements of wave-particle interaction analyses and the ‘triangle-type’ research framework, both of which are initiated and established in ERG
- Sun-synchronous polar-orbiting formation flight at 300-4000 km using multiple “compact” satellites with a weight of about 150-200 kg for each and also micro satellite(s) by international collaborations
- Integrated observations for space plasma particle/wave, fields, FUV/visible emissions, and neutral particles for space physics

FACTORS

(Frontiers of Formation, Acceleration, Coupling, and Transport Mechanisms Observed by the Outer Space Research System)

- WG to be proposed within a half year
- Mission to be proposed around 2020 and realized in mid 2020s by a single Epsilon rocket launch
- Compact(150-200 kg in weight and 700 mm X 700 mm X 900 mm in dimension) and micro satellites with propulsion and precise attitude control systems by ISAS/JAXA and other institutes
- Attitude: 3-axis stabilized, sun-oriented
- Altitude: 300-400 km X 4000 km
- Inclination: 104.5 deg.
- Meridian: Noon-midnight



Three Science Subjects of FACTORS

Elucidation of Magnetosphere-Ionosphere-Thermosphere Coupling Mechanisms by Cutting-Edge Integrated Observations

1. Energy coupling processes between the magnetosphere and the upper ionosphere/thermosphere due to various transport/propagation/mapping mechanisms in the space plasma particles/waves, the electric/magnetic fields, and the field-aligned currents
2. Terrestrial plasma acceleration and upward transport mechanisms caused by the electric fields, plasma waves, and atmospheric heating
3. Response and dynamics in the neutral upper atmosphere due to the energy transport from the space.

Specific Science Targets of FACTORS

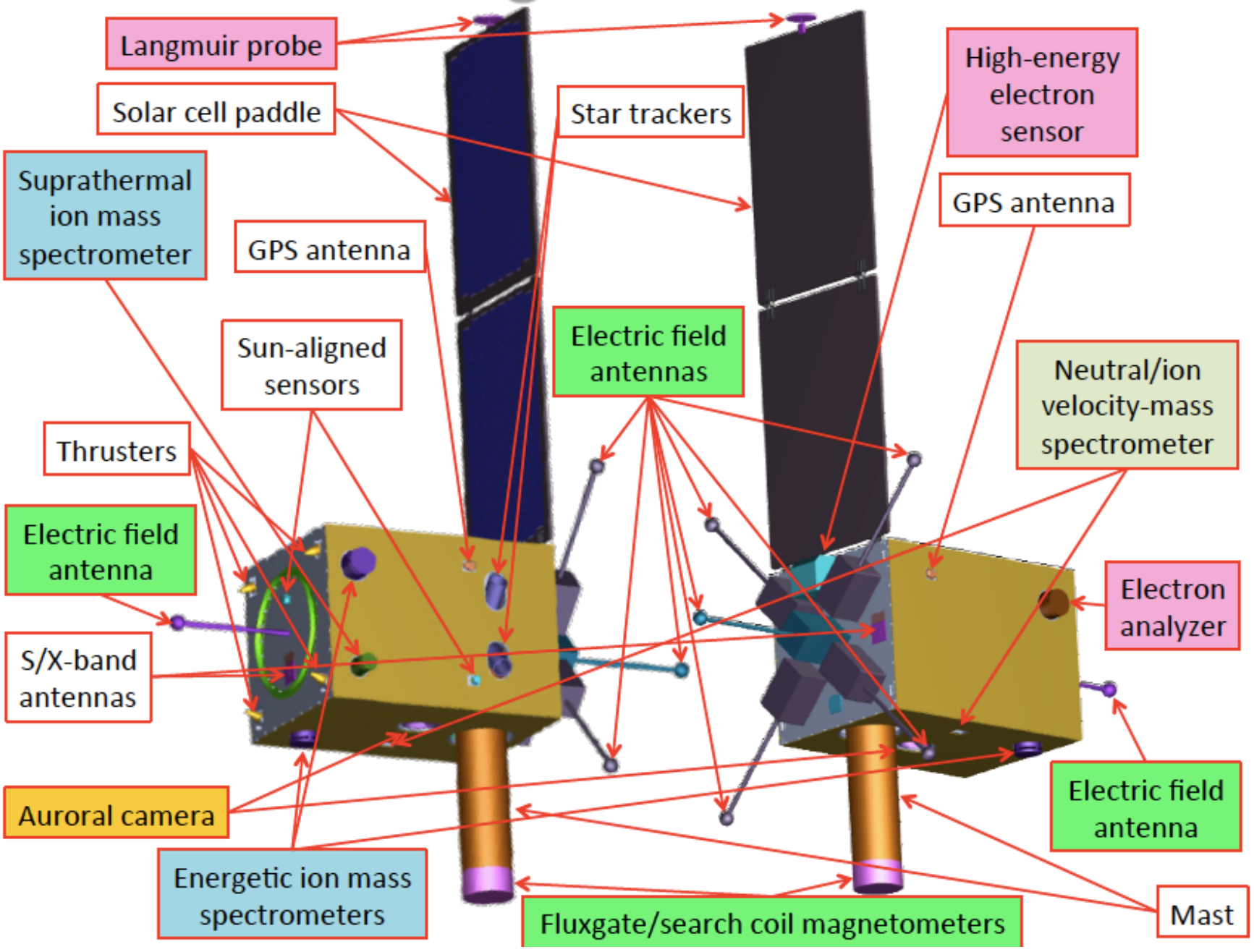
Some detailed subjects could be summarized below:

- Auroral arc formation (growth and decline) associated with quasi-electrostatic parallel potential drop
- Parallel electron acceleration by dispersive Alfven waves(DAW) and EMIC waves
  - Wave-electron interaction
- Transversal ion acceleration probably by electrostatic/ electromagnetic ion cyclotron waves and DAW
  - Wave-ion interaction
- Field-aligned current distribution and variation due to energetic/thermal electron transports
- Neutral atmospheric dynamics due to the couplings with plasma dynamics and field variations
  - Field and plasma/neutral particle interaction

Specification of FACTORS

Configuration	Formation flight by 2 – 3 compact/micro satellites
Launch	During 2026-2028 by a synergy Epsilon rocket from Uchinoura Space Center in Kagoshima, Japan
Orbit	Sun-synchronous Inclination: 104.5 deg. Meridian: Noon-midnight Altitude: 300-400 km X 4000 km
Attitude	Three-axis stabilized, sun-oriented (basically)
Telemetry	S-band for up-link and X-band for down-link
Size/Weight	About $700 \times 700 \times 900$ mm^3 / 150-200 kg for each

Current Configuration of FACTORS



Requirements/Plans on Scientific Instruments

I. Visible and FUV auroral imaging cameras
   - Visible: Lens/Mirror + Filter + (EM)CCD
   - FUV: Mirror + Filter + MCP

II. Low-energy(0.01-30 keV) electron/ion energy analyzers
   - Top-hat + MCP

III. Low-energy(0.01-25 keV) ion energy-mass spectrometer
   - Top-hat + TOF + MCP

IV. Suprathermal(<150 eV) electron energy analyzer

V. Suprathermal(<150 eV) ion energy-mass spectrometer
   - Top-hat + TOF + MCP

VI. High-energy(0.1-2 MeV) electron detector
   - 0.1-2 MeV: Solid-state detector
   - Lower energy: Avalanche photodiode

VII. Atmospheric neutral particle and core ion velocity-mass spectrometer
   - Bennett-type or TOF
   - On/off operation of ion rejection + electron-impact ionization

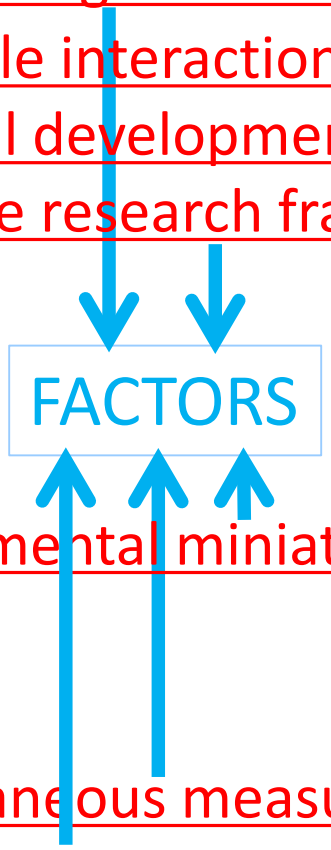
VIII. Plasma wave instrument with three-pair double probes and search coil

IX. Fluxgate magnetometer

X. Langmuir probes

Recent Situation of Milestone Missions in Japanese Space Science Community

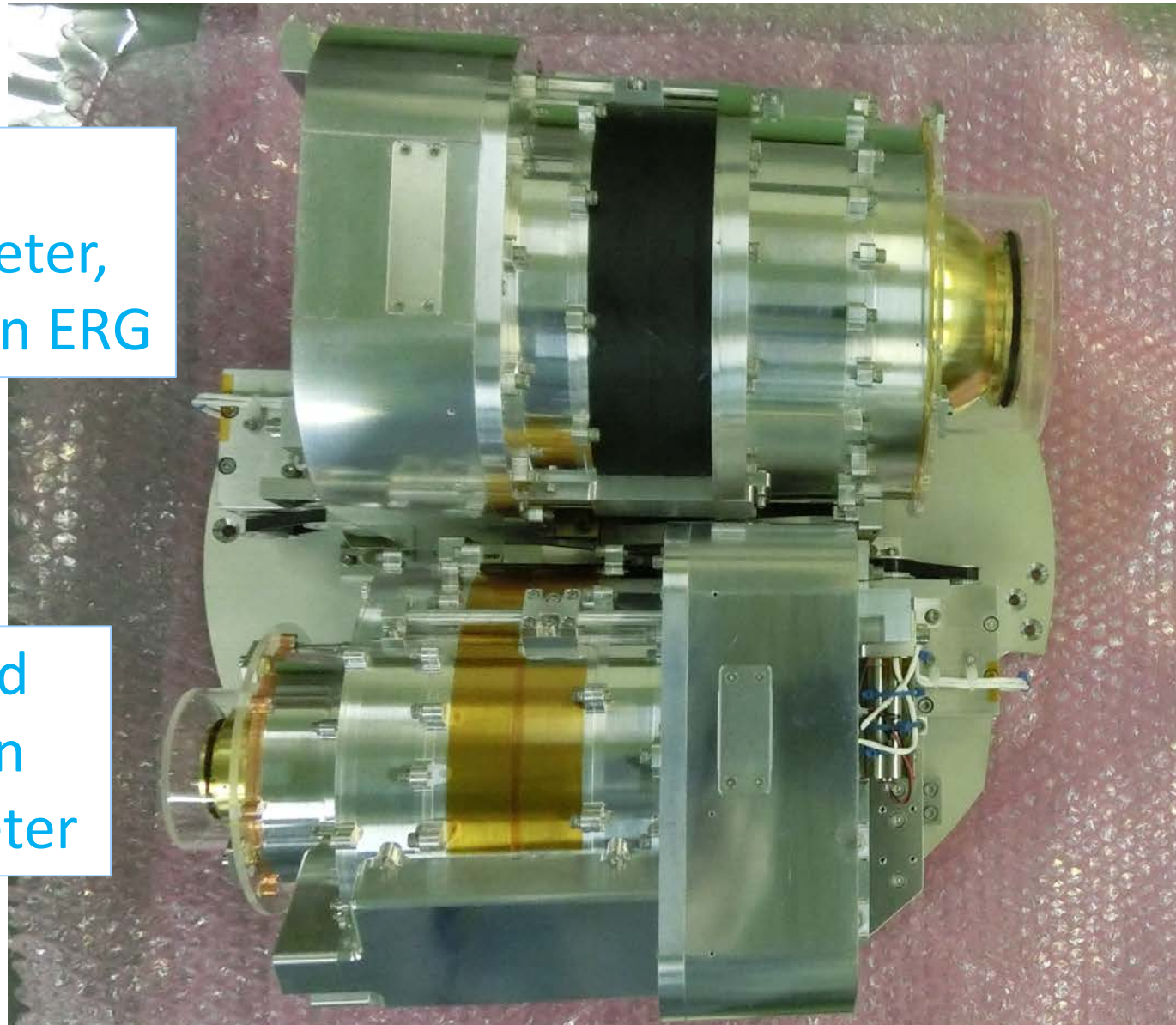
- Terrestrial magnetosphere and space plasma
  - Geotail(on-going)
  - SCOPE(not approved) ——— Formation flight and high-time resolution
  - ERG/Arase(on-going) ——— Wave-particle interaction analysis, Instrumental development, Triangle-type research framework
- Planetary exploration
  - Nozomi for Mars(failed)
  - KAGUYA for moon(succeeded)
  - AKATSUKI for Venus(on-going)
  - Hisaki for UV remote-sensing(on-going)
  - BepiColombo-MMO(to be launched) ——— Instrumental miniaturization
- Polar ionosphere and magnetosphere
  - Akebono(succeeded)
  - Reimei(succeeded) —— Emission-particle simultaneous measurements
  - SS-520-3 rocket(to be launched) ——— Wave-particle interaction analysis, Instrumental development



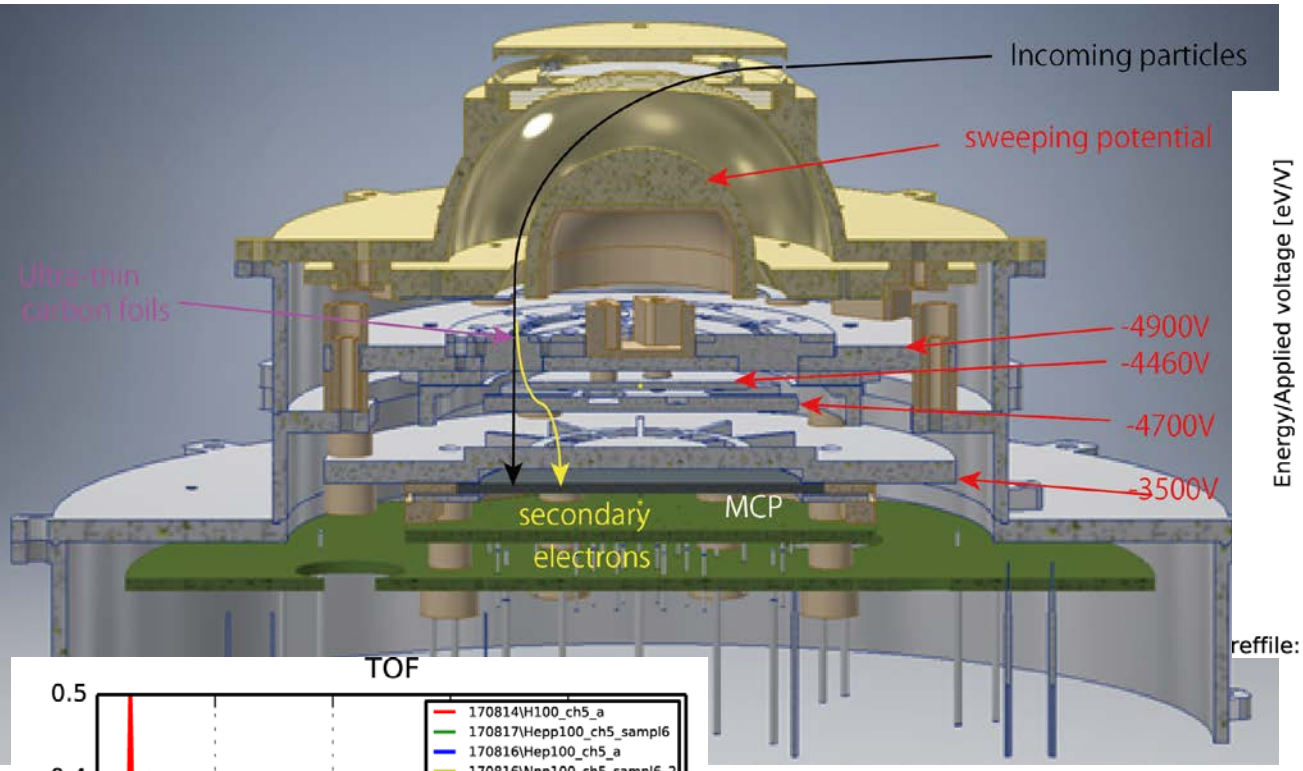
Suprathermal and Low-Energy Ion Mass Spactrometers on SS-520-3 sounding rocket

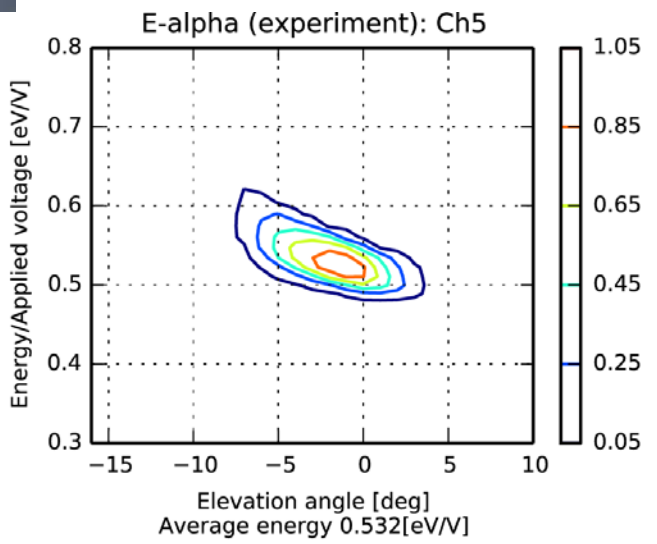
Low-energy ion mass spectrometer, same as LEP-i on ERG

Newly developed suprathermal ion mass spectrometer



Suprathermal Ion Mass Spectrometer for SS-520-3 Sounding Rocket Launched in 2019-2020





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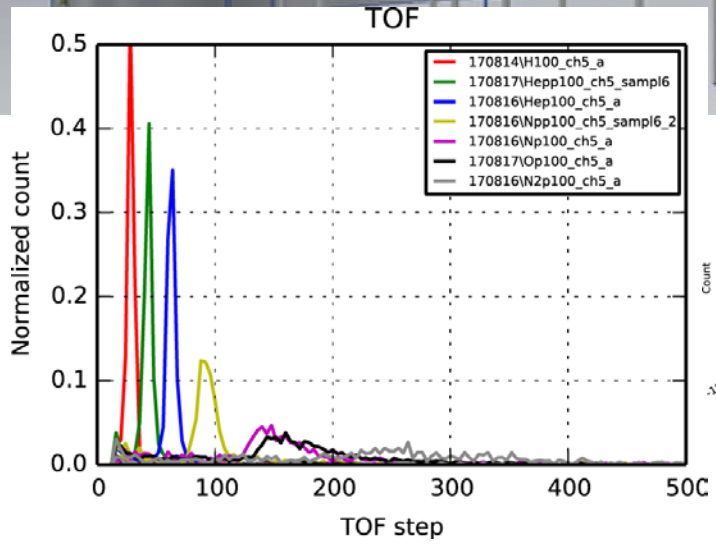
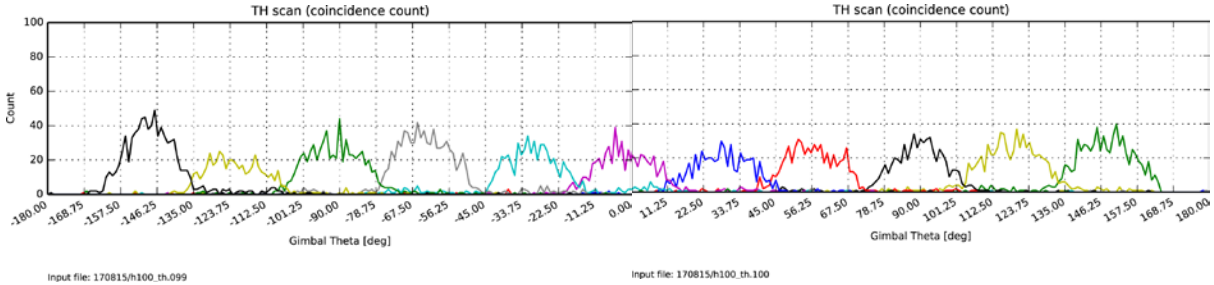
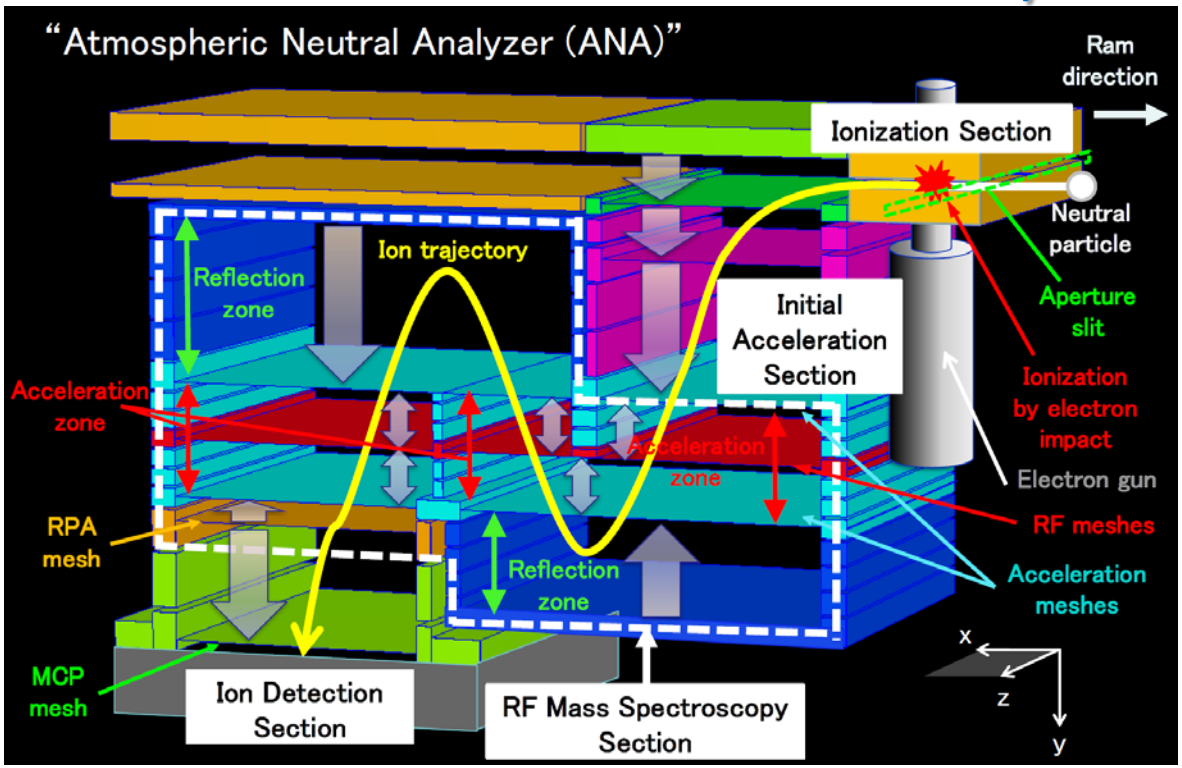
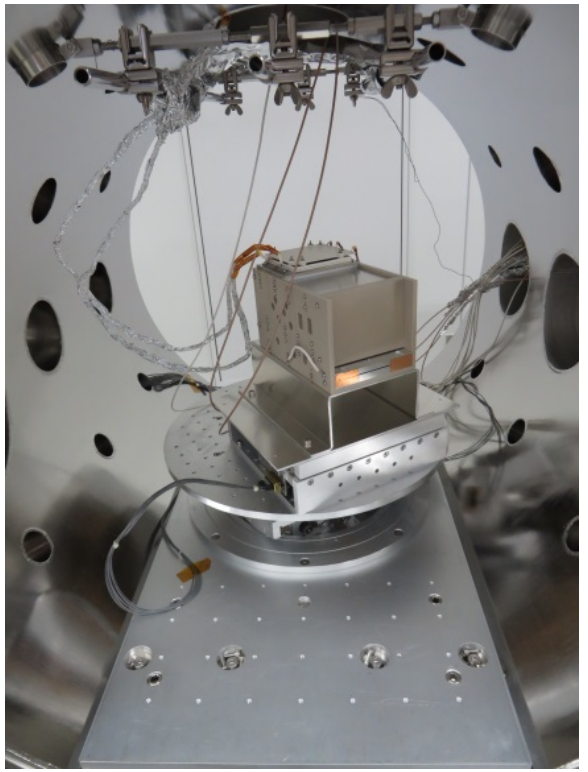


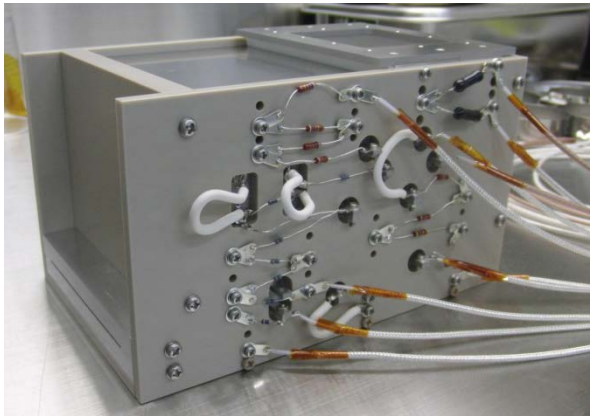


Design and Calibration of Engineering Model of Neutral Particle Velocity-Mass Spectrometer





Parameter	Range	Accuracy
Wind velocity	0-1 km/s	±100 m/s
Mass	1-40 AMU	Δm/m≈0.1
Density	10^5-10^9 cm^{-3}	±30%
Temperature	500-2000 K	±10% or ±100 K
2-D vel. distribution	0-5 km/s + Ram vel.	Δv/v≈0.1

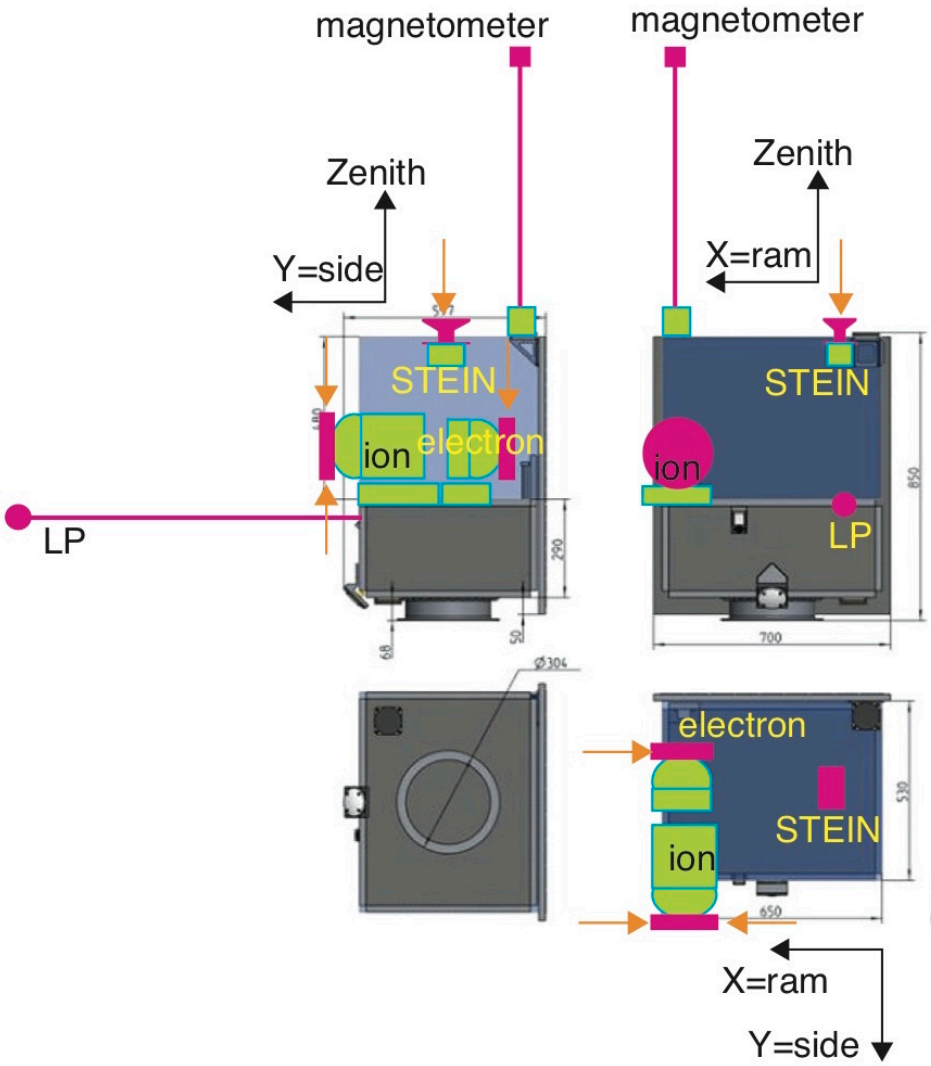


International Collaborations in FACTORS

- Sweden
  - Discussions with IRF, SNSB and OHB
  - Satellite provision possibility for formation flight
  - Instrumental collaboration for in-situ observations
    - Instrument candidates: Energetic neutral atom analyzer, Langmuir probe
    - Collaborative development: Neutral particle velocity/mass spectrometer
  - Simultaneous EISCAT_3D and ALIS_4D observations
  - Satellite tracking contract in ESRANGE with ISAS/JAXA
- US
  - Discussions with LASP of Colorado Univ. and SSL of UC Berkeley
    - Also with GSFC regarding mirror coating technique?
  - Satellite provision possibility for formation flight
  - Instrumental collaboration for in-situ observations
    - Auroral imaging UV camera
  - Science discussions with a future mission definition team applying to NASA?
- Canada
  - Discussions with Univ. of Calgary
  - Instrumental collaboration for in-situ observations
    - Suprathermal ion/electron analyzers
    - Auroral imaging UV camera

An Example of Innosat Configuration for FACTORS collaboration

From the proposal by Dr. Yamauchi of IRF



Under discussions and investigations by SNSB and OHB for the thruster propulsion system keeping the satellite constellation in orbit and the radiation-tolerant satellite bus system

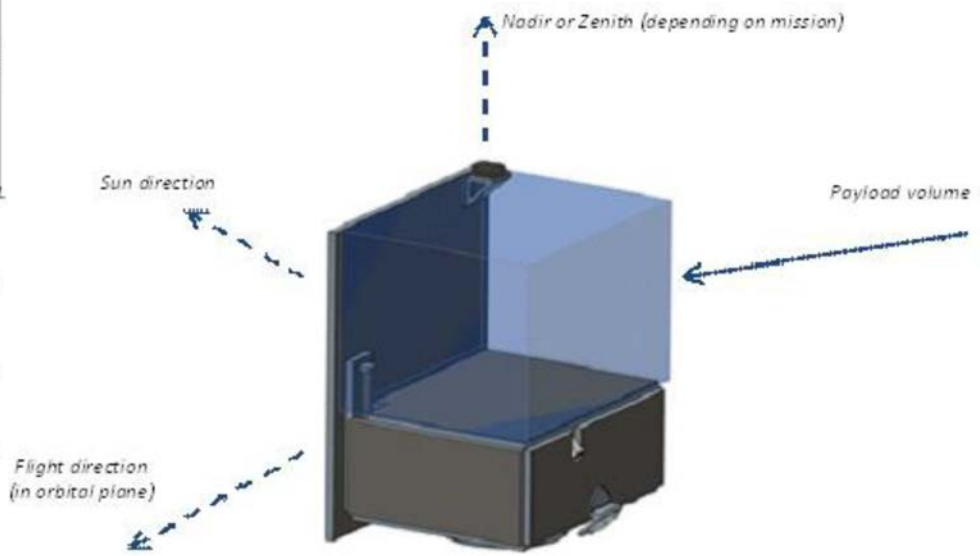


Figure 4-1: Satellite baseline configuration and available payload volume

Summary of the FACTORS Mission

- First Japanese formation flight mission consisting of multiple compact/micro satellites for elucidating the magnetosphere-ionosphere-thermosphere coupling processes/mechanisms
- Next Japanese community/flagship-type mission in a sun-synchronous polar orbit with high-time/spatial resolution
  - After the Japanese INDEX(Reimei) and ERG(Arase) satellite missions
  - To be proposed around 2020 and launched in mid 2020s by a single JAXA synergy Epsilon rocket launch
  - Compact(150 - 200 kg in weight and roughly 700mm X 700mm X 900mm in dimension) and micro satellites with propulsion and precise attitude control systems by ISAS/JAXA and other institutes
  - Attitude: 3-axis stabilized, sun-oriented
  - Altitude: 300-400km X 4000km
  - Inclination: 104.5 deg.
  - Meridian: Noon-midnight

✓WG to be proposed to ISAS/JAXA within a few months

Thank you for your attention.