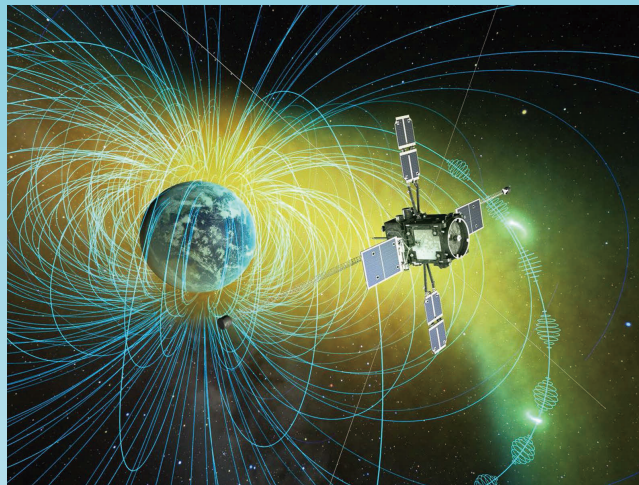


# Earth, Planets and Space

Geospace Exploration by the ERG mission



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## PREFACE

## Open Access



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# Special issue “Geospace Exploration by the ERG mission”

Tsugunobu Nagai<sup>1\*</sup>, Barry Mauk<sup>2</sup>, Ondrej Santolík<sup>3,4</sup>, Takashi Kubota<sup>1</sup> and Takeshi Sakanoi<sup>5</sup>

The exploration of energization and radiation in geospace (ERG) project was developed to understand the fundamental physical processes operating in the Earth's inner magnetosphere. A summary of the ERG project is given in this special issue by Miyoshi et al. (2018a). A central component of this project is the spacecraft Arase, named after the Arase River near the ISAS launch range, (ERG). Arase was launched on December 20, 2016, and it has been operating in a highly elliptical orbit with apogee of 6  $R_E$  and an inclination of 31°. A brief history of the spacecraft development and the technical features of the spacecraft system are given by Nakamura et al. (2018). The spacecraft has an innovated mission network system described by Takashima et al. (2018). Arase hosts nine state-of-the-art scientific instruments to make in situ observations of particles and fields. The multiple instruments for electron measurements are introduced by Kazama et al. (2017), Kasahara et al. (2018a, b), Mitani et al. (2018), and Higashio et al. (2018). The instruments for ion measurements are introduced by Asamura et al. (2018) and Yokota et al. (2017). The magnetic field measurements are described by Matsuoka et al. (2018), and descriptions of the wave and electric fields are provided by Kasahara et al. (2018a, b), Kasaba et al. (2017), Kumamoto et al. (2018), Ozaki et al. (2018), and Matsuda et al. (2018). The interactions between particles and waves, a critical aspect of the physics of the inner magnetosphere, are diagnosed with a software-type wave-particle interaction analyzer, introduced by Katoh et al. (2018) and Hikishima et al. (2018). The ERG project includes a ground-based observation network that is summarized

by Shiokawa et al. (2017). Other key aspects of the ERG project are a program of theory, modeling, and integrating studies described by Seki et al. (2018), and a data processing center called the ERG Science Center, described by Miyoshi et al. (2018b). An example of the data analysis tool development is introduced by Keika et al. (2017). All of these elements together are expected to yield major advancements in our understanding of acceleration, transport, and loss of relativistic electrons in the radiation belts.

## Authors' contributions

All authors of this article served as guest editors for this special issue. All authors read and approved the final manuscript.

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The authors declare that they have no competing interests.

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# Ground-based instruments of the PWING project to investigate dynamics of the inner magnetosphere at subauroral latitudes as a part of the ERG-ground coordinated observation network

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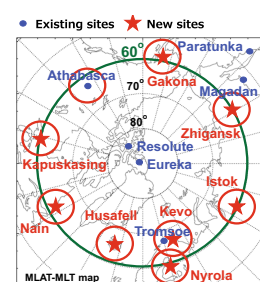
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## Abstract

The plasmas (electrons and ions) in the inner magnetosphere have wide energy ranges from electron volts to mega-electron volts (MeV). These plasmas rotate around the Earth longitudinally due to the gradient and curvature of the geomagnetic field and by the co-rotation motion with timescales from several tens of hours to less than 10 min. They interact with plasma waves at frequencies of mHz to kHz mainly in the equatorial plane of the magnetosphere, obtain energies up to MeV, and are lost into the ionosphere. In order to provide the global distribution and quantitative evaluation of the dynamical variation of these plasmas and waves in the inner magnetosphere, the PWING project (study of dynamical variation of particles and waves in the inner magnetosphere using ground-based network observations, <http://www.isee.nagoya-u.ac.jp/dimr/PWING/>) has been carried out since April 2016. This paper describes the stations and instrumentation of the PWING project. We operate all-sky airglow/aurora imagers, 64-Hz sampling induction magnetometers, 40-kHz sampling loop antennas, and 64-Hz sampling riometers at eight stations at subauroral latitudes ( $\sim 60^\circ$  geomagnetic latitude) in the northern hemisphere, as well as 100-Hz sampling EMCCD cameras at three stations. These stations are distributed longitudinally in Canada, Iceland, Finland, Russia, and Alaska to obtain the longitudinal distribution of plasmas and waves in the inner magnetosphere. This PWING longitudinal network has been developed as a part of the ERG (Arase)-ground coordinated observation network. The ERG (Arase) satellite was launched on December 20, 2016, and has been in full operation since March 2017. We will combine these ground network observations with the ERG (Arase) satellite and global modeling studies. These comprehensive datasets will contribute to the investigation of dynamical variation of particles and waves in the inner magnetosphere, which is one of the most important research topics in recent space physics, and the outcome of our research will improve safe and secure use of geospace around the Earth.

**Keywords:** All-sky airglow/aurora imager, Induction magnetometer, Riometer, Loop antenna, EMCCD camera, Inner magnetosphere, SAR arc, Magnetospheric ELF/VLF wave, EMIC wave, Radiation belts



Graphical abstract

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# Low-energy particle experiments–electron analyzer (LEPe) onboard the Arase spacecraft

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## Abstract

In this report, we describe the low-energy electron instrument LEPe (low-energy particle experiments–electron analyzer) onboard the Arase (ERG) spacecraft. The instrument measures a three-dimensional distribution function of electrons with energies of  $\sim 19$  eV–19 keV. Electrons in this energy range dominate in the inner magnetosphere, and measurement of such electrons is important in terms of understanding the magnetospheric dynamics and wave–particle interaction. The instrument employs a toroidal tophat electrostatic energy analyzer with a passive 6-mm aluminum shield. To minimize background radiation effects, the analyzer has a background channel, which monitors counts produced by background radiation. Background counts are then subtracted from measured counts. Electronic components are radiation tolerant, and 5-mm-thick shielding of the electronics housing ensures that the total dose is less than 100 kRad for the one-year nominal mission lifetime. The first in-space measurement test was done on February 12, 2017, showing that the instrument functions well. On February 27, the first all-instrument run test was done, and the LEPe instrument measured an energy dispersion event probably related to a substorm injection occurring immediately before the instrument turn-on. These initial results indicate that the instrument works fine in space, and the measurement performance is good for science purposes.

**Keywords:** Low-energy electron measurement, Particle instrumentation, Inner magnetosphere



Graphical abstract

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# Medium-energy particle experiments–ion mass analyzer (MEP-i) onboard ERG (Arase)

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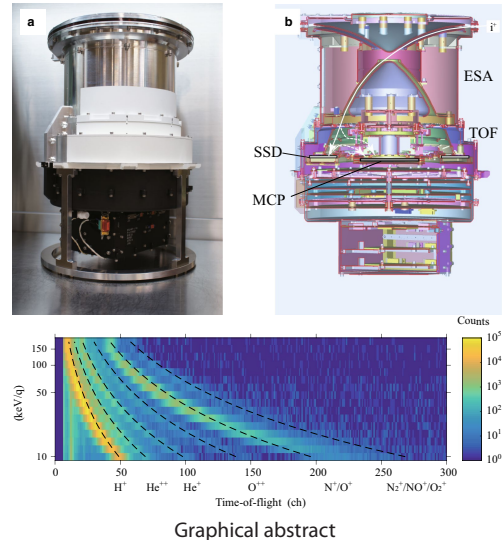
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## Abstract

The medium-energy particle experiments–ion mass analyzer (MEP-i) was developed for the exploration of energization and radiation in geospace (ERG) mission (Arase), in order to measure the three-dimensional distribution functions of the inner-magnetospheric ions in the medium energy range between 10 and 180 keV/q. The energy, mass, and charge state of each ion are determined by a combination of an electrostatic energy/charge analyzer, a time-of-flight mass/charge analyzer, and energy-sensitive solid-state detectors. This paper describes the instrumentation of the MEP-i, data products, and observation results during a magnetic storm.

**Keywords:** ERG, Radiation belts, Medium-energy particles, Mass analyses



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# Wire Probe Antenna (WPT) and Electric Field Detector (EFD) of Plasma Wave Experiment (PWE) aboard the Arase satellite: specifications and initial evaluation results

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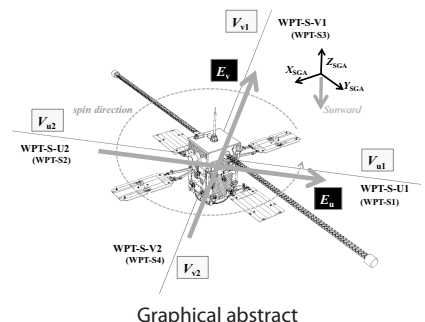
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## Abstract

This paper summarizes the specifications and initial evaluation results of Wire Probe Antenna (WPT) and Electric Field Detector (EFD), the key components for the electric field measurement of the Plasma Wave Experiment (PWE) aboard the Arase (ERG) satellite. WPT consists of two pairs of dipole antennas with  $\sim 31$ -m tip-to-tip length. Each antenna element has a spherical probe (60 mm diameter) at each end of the wire (15 m length). They are extended orthogonally in the spin plane of the spacecraft, which is roughly perpendicular to the Sun and enables to measure the electric field in the frequency range of DC to 10 MHz. This system is almost identical to the WPT of Plasma Wave Investigation aboard the BepiColombo Mercury Magnetospheric Orbiter, except for the material of the spherical probe (ERG: Al alloy, MMO: Ti alloy). EFD is a part of the EWO (EFD/WFC/OFA) receiver and measures the 2-ch electric field at a sampling rate of 512 Hz (dynamic range:  $\pm 200$  mV/m) and the 4-ch spacecraft potential at a sampling rate of 128 Hz (dynamic range:  $\pm 100$  V and  $\pm 3$  V/m), with the bias control capability of WPT. The electric field waveform provides (1) fundamental information about the plasma dynamics and accelerations and (2) the characteristics of MHD and ion waves in various magnetospheric statuses with the magnetic field measured by MGF and PWE-MS. The spacecraft potential provides information on thermal electron plasma variations and structure combined with the electron density obtained from the upper hybrid resonance frequency provided by PWE-HFA. EFD has two data modes. The continuous (medium-mode) data are provided as (1) 2-ch waveforms at 64 Hz (in apoapsis mode,  $L > 4$ ) or 256 Hz (in periapsis mode,  $L < 4$ ), (2) 1-ch spectrum within 1–232 Hz with 1-s resolution, and (3) 4-ch spacecraft potential at 8 Hz. The burst (high-mode) data are intermittently obtained as (4) 2-ch waveforms at 512 Hz and (5) 4-ch spacecraft potential at 128 Hz and downloaded with the WFC-E/B datasets after the selection. This paper also shows the initial evaluation results in the initial observation phase.

**Keywords:** Electric field, Plasma wave, Spacecraft potential, Electron density and temperature, Wire Probe Antenna (WPT), Electric Field Detector (EFD), Plasma Wave Experiment (PWE), Arase spacecraft



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# Software-type Wave–Particle Interaction Analyzer on board the Arase satellite

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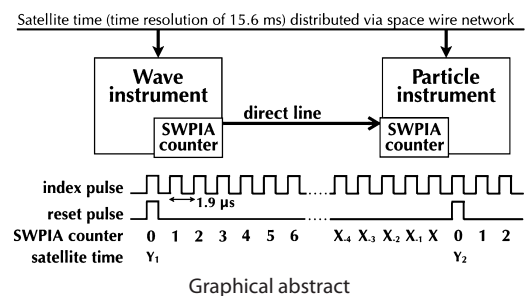
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## Abstract

We describe the principles of the Wave–Particle Interaction Analyzer (WPIA) and the implementation of the Software-type WPIA (S-WPIA) on the Arase satellite. The WPIA is a new type of instrument for the direct and quantitative measurement of wave–particle interactions. The S-WPIA is installed on the Arase satellite as a software function running on the mission data processor. The S-WPIA on board the Arase satellite uses an electromagnetic field waveform that is measured by the waveform capture receiver of the plasma wave experiment (PWE), and the velocity vectors of electrons detected by the medium-energy particle experiment–electron analyzer (MEP-e), the high-energy electron experiment (HEP), and the extremely high-energy electron experiment (XEP). The prime objective of the S-WPIA is to measure the energy exchange between whistler-mode chorus emissions and energetic electrons in the inner magnetosphere. It is essential for the S-WPIA to synchronize instruments to a relative time accuracy better than the time period of the plasma wave oscillations. Since the typical frequency of chorus emissions in the inner magnetosphere is a few kHz, a relative time accuracy of better than 10  $\mu$ s is required in order to measure the relative phase angle between the wave and velocity vectors. In the Arase satellite, a dedicated system has been developed to realize the time resolution required for inter-instrument communication. Here, both the time index distributed over all instruments through the satellite system and an S-WPIA clock signal are used, that are distributed from the PWE to the MEP-e, HEP, and XEP through a direct line, for the synchronization of instruments within a relative time accuracy of a few  $\mu$ s. We also estimate the number of particles required to obtain statistically significant results with the S-WPIA and the expected accumulation time by referring to the specifications of the MEP-e and assuming a count rate for each detector.

**Keywords:** Radiation belts, Magnetosphere, Whistler-mode chorus, Wave–particle interactions



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# Theory, modeling, and integrated studies in the Arase (ERG) project

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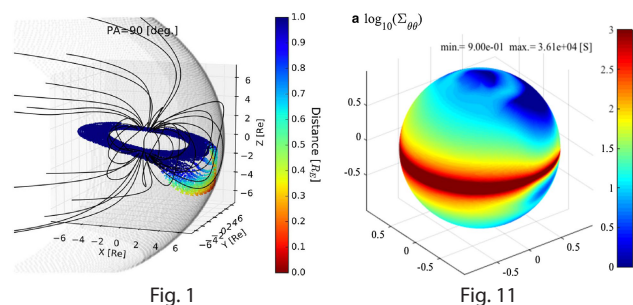
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## Abstract

Understanding of underlying mechanisms of drastic variations of the near-Earth space (geospace) is one of the current focuses of the magnetospheric physics. The science target of the geospace research project Exploration of energization and Radiation in Geospace (ERG) is to understand the geospace variations with a focus on the relativistic electron acceleration and loss processes. In order to achieve the goal, the ERG project consists of the three parts: the Arase (ERG) satellite, ground-based observations, and theory/modeling/integrated studies. The role of theory/modeling/integrated studies part is to promote relevant theoretical and simulation studies as well as integrated data analysis to combine different kinds of observations and modeling. Here we provide technical reports on simulation and empirical models related to the ERG project together with their roles in the integrated studies of dynamic geospace variations. The simulation and empirical models covered include the radial diffusion model of the radiation belt electrons, GEMSIS-RB and RBW models, CIMI model with global MHD simulation REPPU, GEMSIS-RC model, plasmasphere thermosphere model, self-consistent wave–particle interaction simulations (electron hybrid code and ion hybrid code), the ionospheric electric potential (GEMSIS-POT) model, and SuperDARN electric field models with data assimilation. ERG (Arase) science center tools to support integrated studies with various kinds of data are also briefly introduced.

**Keywords:** Inner magnetosphere, Numerical simulation/modeling, Geospace, Magnetic storms, Arase/ERG



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# The ARASE (ERG) magnetic field investigation

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## Abstract

The fluxgate magnetometer for the Arose (ERG) spacecraft mission was built to investigate particle acceleration processes in the inner magnetosphere. Precise measurements of the field intensity and direction are essential in studying the motion of particles, the properties of waves interacting with the particles, and magnetic field variations induced by electric currents. By observing temporal field variations, we will more deeply understand magnetohydrodynamic and electromagnetic ion-cyclotron waves in the ultra-low-frequency range, which can cause production and loss of relativistic electrons and ring-current particles. The hardware and software designs of the Magnetic Field Experiment (MGF) were optimized to meet the requirements for studying these phenomena. The MGF makes measurements at a sampling rate of 256 vectors/s, and the data are averaged onboard to fit the telemetry budget. The magnetometer switches the dynamic range between  $\pm 8000$  and  $\pm 60,000$  nT, depending on the local magnetic field intensity. The experiment is calibrated by preflight tests and through analysis of in-orbit data. MGF data are edited into files with a common data file format, archived on a data server, and made available to the science community. Magnetic field observation by the MGF will significantly improve our knowledge of the growth and decay of radiation belts and ring currents, as well as the dynamics of geospace storms.

**Keywords:** EMIC wave, Geospace, Magnetic field, Magnetometer, Radiation belts, Ring current, ULF wave



Graphical abstract

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# Medium-energy particle experiments—electron analyzer (MEP-e) for the exploration of energization and radiation in geospace (ERG) mission

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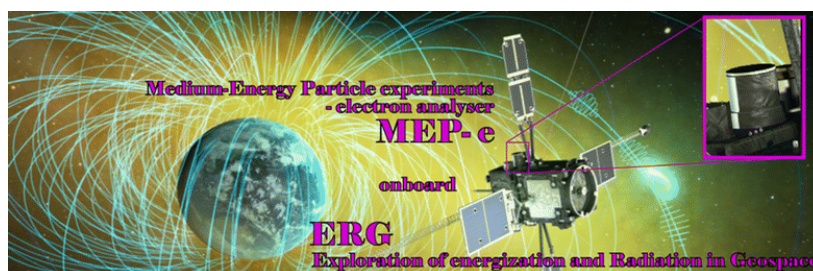
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## Abstract

The medium-energy particle experiments—electron analyzer onboard the exploration of energization and radiation in geospace spacecraft measures the energy and direction of each incoming electron in the energy range of 7–87 keV. The sensor covers a  $2\pi$ -radian disklike field of view with 16 detectors, and the full solid angle coverage is achieved through the spacecraft's spin motion. The electron energy is independently measured by both an electrostatic analyzer and avalanche photodiodes, enabling significant background reduction. We describe the technical approach, data output, and examples of initial observations.

**Keywords:** Radiation belts, ERG spacecraft, Medium-energy particles



Graphical abstract

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# Low-energy particle experiments–ion mass analyzer (LEPi) onboard the ERG (Arase) satellite

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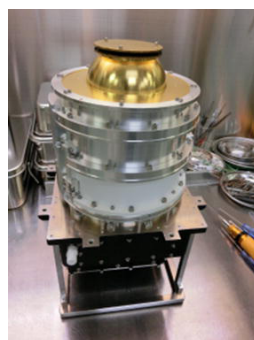
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## Abstract

Low-energy ion experiments–ion mass analyzer (LEPi) is one of the particle instruments onboard the ERG satellite. LEPi is an ion energy-mass spectrometer which covers the range of particle energies from  $< 0.01$  to 25 keV/q. Species of incoming ions are discriminated by a combination of electrostatic energy-per-charge analysis and the time-of-flight technique. The sensor has a planar field-of-view, which provides  $4\pi$  steradian coverage by using the spin motion of the satellite. LEPi started its nominal observation after the initial checkout and commissioning phase in space.

**Keywords:** ERG satellite, Ion analyzer



Graphical abstract

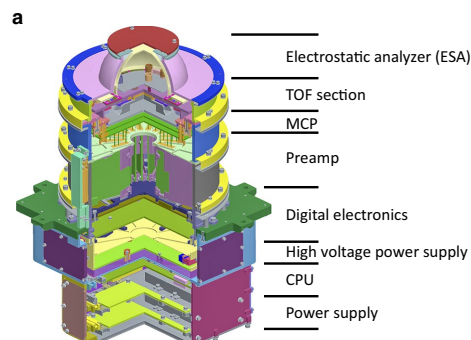


Fig. 3

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# Design of a mission network system using SpaceWire for scientific payloads onboard the Arase spacecraft

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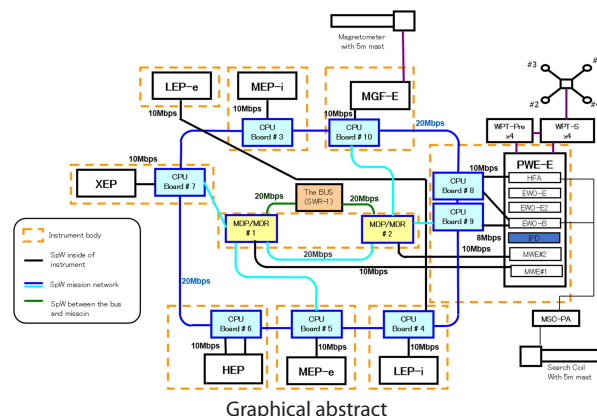


## Abstract

Arase is a small scientific satellite program conducted by the Institute of Space and Astronautical Science/Japan Aerospace Exploration Agency, which is dedicated to the detailed study of the radiation belts around Earth through in situ observations. In particular, the goal is to directly observe the interaction between plasma waves and particles, which cause the generation of high-energy electrons. To observe the waves and particles in detail, we must record large volumes of burst data with high transmission rates through onboard mission network systems.

For this purpose, we developed a high-speed and highly reliable mission network based on SpaceWire, as well as a new and large memory data recorder equipped with a data search function based on observation time (the time index, TI, is the satellite time starting from when the spacecraft is powered on.) with respect to the orbital data generated in large quantities. By adopting a new transaction concept of a ring topology network with SpaceWire, we could secure a redundant mission network system without using large routers and having to suppress the increase in cable weight. We confirmed that their orbit performs as designed.

**Keywords:** The ERG project, Radiation belts, Geospace, SpaceWire, Mission data processor



Graphical abstract

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# Onboard software of Plasma Wave Experiment aboard Arase: instrument management and signal processing of Waveform Capture/Onboard Frequency Analyzer

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## Abstract

We developed the onboard processing software for the Plasma Wave Experiment (PWE) onboard the Exploration of energization and Radiation in Geospace, Arase satellite. The PWE instrument has three receivers: Electric Field Detector, Waveform Capture/Onboard Frequency Analyzer (WFC/OFA), and the High-Frequency Analyzer. We designed a pseudo-parallel processing scheme with a time-sharing system and achieved simultaneous signal processing for each receiver. Since electric and magnetic field signals are processed by the different CPUs, we developed a synchronized observation system by using shared packets on the mission network. The OFA continuously measures the power spectra, spectral matrices, and complex spectra. The OFA obtains not only the entire ELF/VLF plasma waves' activity but also the detailed properties (e.g., propagation direction and polarization) of the observed plasma waves. We performed simultaneous observation of electric and magnetic field data and successfully obtained clear wave properties of whistler-mode chorus waves using these data. In order to measure raw waveforms, we developed two modes for the WFC, 'chorus burst mode' (65,536 samples/s) and 'EMIC burst mode' (1024 samples/s), for the purpose of the measurement of the whistler-mode chorus waves (typically in a frequency range from several hundred Hz to several kHz) and the EMIC waves (typically in a frequency range from a few Hz to several hundred Hz), respectively. We successfully obtained the waveforms of electric and magnetic fields of whistler-mode chorus waves and ion cyclotron mode waves along the Arase's orbit. We also designed the software-type wave-particle interaction analyzer mode. In this mode, we measure electric and magnetic field waveforms continuously and transfer them to the mission data recorder onboard the Arase satellite. We also installed an onboard signal calibration function (onboard SoftWare CALibration; SWCAL). We performed onboard electric circuit diagnostics and antenna impedance measurement of the wire-probe antennas along the orbit. We utilize the results obtained using the SWCAL function when we calibrate the spectra and waveforms obtained by the PWE.

**Keywords:** Arase satellite, ERG, PWE, Plasma wave, Geospace, Radiation belt, Onboard processing, Chorus wave, EMIC wave, Magnetosonic wave

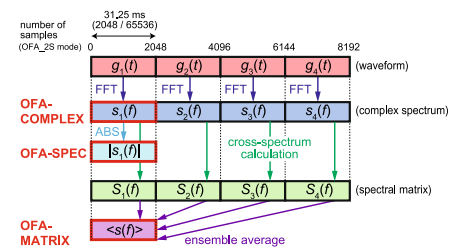


Fig. 7

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# Magnetic Search Coil (MSC) of Plasma Wave Experiment (PWE) aboard the Arase (ERG) satellite

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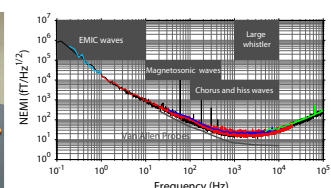
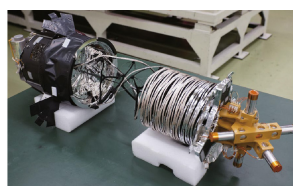
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## Abstract

This paper presents detailed performance values of the Magnetic Search Coil (MSC) that is part of the Plasma Wave Experiment on board the Arase (ERG) satellite. The MSC consists of a three-axis search coil magnetometer with a 200-mm-long magnetic core. The MSC plays a central role in the magnetic field observations, particularly for whistler mode chorus and hiss waves in a few kHz frequency range, which may cause local acceleration and/or rapid loss of radiation belt electrons. Accordingly, the MSC was carefully designed and developed to operate well in harsh radiation environments. To ascertain the wave-normal vectors, polarizations, and refractive indices of the plasma waves in a wide frequency band, the output signals detected by the MSC are fed into the two different wave receivers: one is the WaveForm Capture/Onboard Frequency Analyzer for waveform and spectrum observations in the frequency range from a few Hz up to 20 kHz, and the other is the High Frequency Analyzer for spectrum observations in the frequency range from 10 to 100 kHz. The noise equivalent magnetic induction of the MSC is 20 fT/Hz<sup>1/2</sup> at a frequency of 2 kHz, and the null depth of directionality is -40 dB, which is equivalent to an angular error less than 1°. The MSC on board the Arase satellite is the first experiment using a current-sensitive preamplifier for probing the plasma waves in the radiation belts.

**Keywords:** Search coil magnetometer, Arase (ERG) satellite, Plasma waves, Radiation belts, Geospace



Graphical abstract

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# High-energy electron experiments (HEP) aboard the ERG (Arase) satellite

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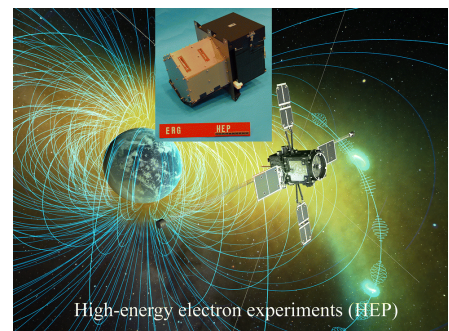
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## Abstract

This paper reports the design, calibration, and operation of high-energy electron experiments (HEP) aboard the exploration of energization and radiation in geospace (ERG) satellite. HEP detects 70 keV–2 MeV electrons and generates a three-dimensional velocity distribution for these electrons in every period of the satellite's rotation. Electrons are detected by two instruments, namely HEP-L and HEP-H, which differ in their geometric factor (G-factor) and range of energies they detect. HEP-L detects 70 keV–1 MeV electrons and its G-factor is  $9.3 \times 10^{-4} \text{ cm}^2 \text{ sr}$  at maximum, while HEP-H observes 0.7–2 MeV electrons and its G-factor is  $9.3 \times 10^{-3} \text{ cm}^2 \text{ sr}$  at maximum. The instruments utilize silicon strip detectors and application-specific integrated circuits to readout the incident charge signal from each strip. Before the launch, we calibrated the detectors by measuring the energy spectra of all strips using  $\gamma$ -ray sources. To evaluate the overall performance of the HEP instruments, we measured the energy spectra and angular responses with electron beams. After HEP was first put into operation, on February 2, 2017, it was demonstrated that the instruments performed normally. HEP began its exploratory observations with regard to energization and radiation in geospace in late March 2017. The initial results of the in-orbit observations are introduced briefly in this paper.

**Keywords:** ERG, Arase, Radiation belts, High-energy electrons



Graphical abstract

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# Data processing in Software-type Wave–Particle Interaction Analyzer onboard the Arase satellite

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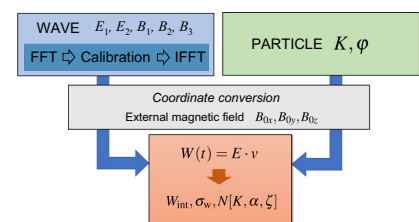
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## Abstract

The software-type wave–particle interaction analyzer (S-WPIA) is an instrument package onboard the Arase satellite, which studies the magnetosphere. The S-WPIA represents a new method for directly observing wave–particle interactions onboard a spacecraft in a space plasma environment. The main objective of the S-WPIA is to quantitatively detect wave–particle interactions associated with whistler-mode chorus emissions and electrons over a wide energy range (from several keV to several MeV). The quantity of energy exchanges between waves and particles can be represented as the inner product of the wave electric-field vector and the particle velocity vector. The S-WPIA requires accurate measurement of the phase difference between wave and particle gyration. The leading edge of the S-WPIA system allows us to collect comprehensive information, including the detection time, energy, and incoming direction of individual particles and instantaneous-wave electric and magnetic fields, at a high sampling rate. All the collected particle and waveform data are stored in the onboard large-volume data storage. The S-WPIA executes calculations asynchronously using the collected electric and magnetic wave data, data acquired from multiple particle instruments, and ambient magnetic-field data. The S-WPIA has the role of handling large amounts of raw data that are dedicated to calculations of the S-WPIA. Then, the results are transferred to the ground station. This paper describes the design of the S-WPIA and its calculations in detail, as implemented onboard Arase.

**Keywords:** Wave–particle interaction, Onboard processing, Inner magnetosphere



Graphical abstract

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# High Frequency Analyzer (HFA) of Plasma Wave Experiment (PWE) onboard the Arase spacecraft

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## Abstract

The High Frequency Analyzer (HFA) is a subsystem of the Plasma Wave Experiment onboard the Arase (ERG) spacecraft. The main purposes of the HFA include (1) determining the electron number density around the spacecraft from observations of upper hybrid resonance (UHR) waves, (2) measuring the electromagnetic field component of whistler-mode chorus in a frequency range above 20 kHz, and (3) observing radio and plasma waves excited in the storm-time magnetosphere. Two components of AC electric fields detected by Wire Probe Antenna and one component of AC magnetic fields detected by Magnetic Search Coils are fed to the HFA. By applying analog and digital signal processing in the HFA, the spectrograms of two electric fields (EE mode) or one electric field and one magnetic field (EB mode) in a frequency range from 10 kHz to 10 MHz are obtained at an interval of 8 s. For the observation of plasmopause, the HFA can also be operated in PP (plasmopause) mode, in which spectrograms of one electric field component below 1 MHz are obtained at an interval of 1 s. In the initial HFA operations from January to July, 2017, the following results are obtained: (1) UHR waves, auroral kilometric radiation (AKR), whistler-mode chorus, electrostatic electron cyclotron harmonic waves, and nonthermal terrestrial continuum radiation were observed by the HFA in geomagnetically quiet and disturbed conditions. (2) In the test operations of the polarization observations on June 10, 2017, the fundamental R-X and L-O mode AKR and the second-harmonic R-X mode AKR from different sources in the northern polar region were observed. (3) The semiautomatic UHR frequency identification by the computer and a human operator was applied to the HFA spectrograms. In the identification by the computer, we used an algorithm for narrowing down the candidates of UHR frequency by checking intensity and bandwidth. Then, the identified UHR frequency by the computer was checked and corrected if needed by the human operator. Electron number density derived from the determined UHR frequency will be useful for the investigation of the storm-time evolution of the plasmasphere and topside ionosphere.

**Keywords:** The Arase (ERG) spacecraft, Plasma Wave Experiment (PWE), High Frequency Analyzer (HFA), Upper hybrid resonance (UHR) wave, Auroral kilometric radiation (AKR), Whistler-mode chorus, Electrostatic electron cyclotron harmonic (ESCH) wave, Nonthermal terrestrial continuum (NTC) radiation, Electron number density, Plasmasphere

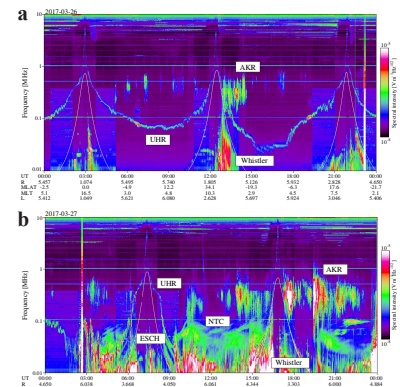


Fig. 2

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# The Plasma Wave Experiment (PWE) on board the Arase (ERG) satellite

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## Abstract

The Exploration of energization and Radiation in Geospace (ERG) project aims to study acceleration and loss mechanisms of relativistic electrons around the Earth. The Arase (ERG) satellite was launched on December 20, 2016, to explore in the heart of the Earth's radiation belt. In the present paper, we introduce the specifications of the Plasma Wave Experiment (PWE) on board the Arase satellite. In the inner magnetosphere, plasma waves, such as the whistler-mode chorus, electromagnetic ion cyclotron wave, and magnetosonic wave, are expected to interact with particles over a wide energy range and contribute to high-energy particle loss and/or acceleration processes. Thermal plasma density is another key parameter because it controls the dispersion relation of plasma waves, which affects wave-particle interaction conditions and wave propagation characteristics. The DC electric field also plays an important role in controlling the global dynamics of the inner magnetosphere. The PWE, which consists of an orthogonal electric field sensor (WPT; wire probe antenna), a triaxial magnetic sensor (MSC; magnetic search coil), and receivers named electric field detector (EFD), waveform capture and onboard frequency analyzer (WFC/OFA), and high-frequency analyzer (HFA), was developed to measure the DC electric field and plasma waves in the inner magnetosphere. Using these sensors and receivers, the PWE covers a wide frequency range from DC to 10 MHz for electric fields and from a few Hz to 100 kHz for magnetic fields. We produce continuous ELF/VLF/HF range wave spectra and ELF range waveforms for 24 h each day. We also produce spectral matrices as continuous data for wave direction finding. In addition, we intermittently produce two types of waveform burst data, "chorus burst" and "EMIC burst." We also input raw waveform data into the software-type wave-particle interaction analyzer (S-WPIA), which derives direct correlation between waves and particles. Finally, we introduce our PWE observation strategy and provide some initial results.

**Keywords:** Plasma wave, Radiation belt, Geospace, Inner magnetosphere, Chorus

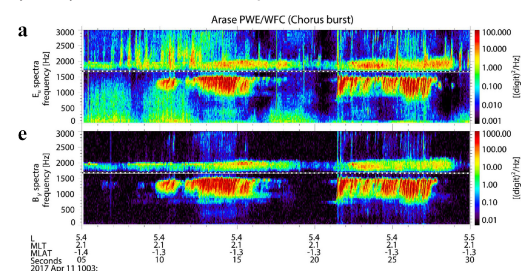


Fig. 20

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## Geospace exploration project ERG

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### Abstract

The Exploration of energization and Radiation in Geospace (ERG) project explores the acceleration, transport, and loss of relativistic electrons in the radiation belts and the dynamics for geospace storms. This project consists of three research teams for satellite observation, ground-based network observation, and integrated data analysis/simulation. This synergetic approach is essential for obtaining a comprehensive understanding of the relativistic electron generation/loss processes of the radiation belts as well as geospace storms through cross-energy/cross-regional couplings, in which different plasma/particle populations and regions are strongly coupled with each other. This paper gives an overview of the ERG project and presents the initial results from the ERG (Arase) satellite.

**Keywords:** The ERG project, The ERG (Arase) satellite, The radiation belts, Geospace

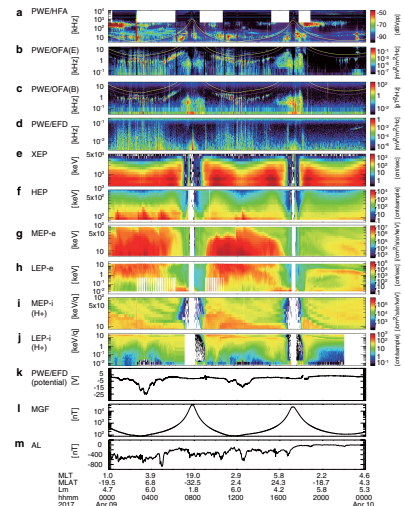


Fig. 6

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## Exploration of energization and radiation in geospace (ERG): challenges, development, and operation of satellite systems

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### Abstract

The exploration of energization and radiation in geospace (ERG) satellite, nicknamed “Arase,” is the second satellite in a series of small scientific satellites created by the Institute of Space and Astronautical Science of the Japan Aerospace Exploration Agency. It was launched on December 20, 2016, by the Epsilon launch vehicle. The purpose of the ERG project is to investigate how high-energy (over MeV) electrons in the radiation belts surrounding Earth are generated and lost by monitoring the interactions between plasma waves and electrically charged particles. To measure these physical processes in situ, the ERG satellite traverses the heart of the radiation belts. The orbit of the ERG is highly elliptical and varies due to the perturbation force: the apogee altitude is approximately 32,200–32,300 km, and the perigee altitude is 340–440 km. In this study, we introduce the scientific background for this project and four major challenges that need to be addressed to effectively carry out this scientific mission with a small satellite: (1) dealing with harsh environmental conditions in orbit and electromagnetic compatibility issues, (2) spin attitude stabilization and avoiding excitation of the libration by flexible structures, (3) attaining an appropriate balance between the mission requirements and the limited resources of the small satellite, and (4) the adaptation and use of a flexible standardized bus. In this context, we describe the development process and the flight operations for the satellite, which is currently working as designed and obtaining excellent data in its mission.

**Keywords:** ERG, Arase, Radiation belts, Van Allen belts, Geospace, Small satellite, Project

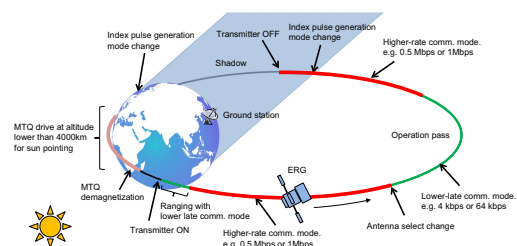


Fig. 17

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# The extremely high-energy electron experiment (XEP) onboard the Arase (ERG) satellite

Nana Higashio\*, Takeshi Takashima, Iku Shinohara and Haruhisa Matsumoto

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## Abstract

The extremely high-energy electron experiment (XEP) onboard the Arase (ERG) satellite is designed to measure high-energy electrons in the Earth's radiation belts. The XEP was developed by taking advantage of our technical heritage of high-energy particle detectors that are onboard Earth observation satellites of the Japan Aerospace Exploration Agency (JAXA) as the radiation monitor. The main target of the XEP is to precisely measure variations of relativistic electrons in the outer radiation belt even during magnetic storms. The measurement is scientifically required to address physical mechanisms of electron acceleration and loss. The XEP consists of five solid-state silicon detectors (SSDs) and a single-crystal inorganic scintillator of cerium-doped gadolinium orthosilicate (GSO) to measure electrons in the energy range of 0.4–20 MeV and has a 20° single field of view (FOV). It is also equipped with a plastic scintillator that surrounds the GSO scintillator to prevent particles from entering the detectors from outside the FOV. The XEP has started its observation of relativistic electrons and has successfully observed dynamic variations of relativistic electron fluxes in the outer radiation belt during magnetic storms. This paper describes the instrumentation of the XEP and presents an example of initial observation results.

**Keywords:** ERG, Radiation belts, Extremely high-energy electron experiment

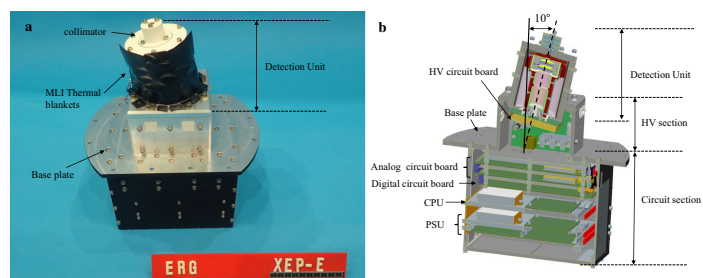


Fig. 1

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# Visualization tool for three-dimensional plasma velocity distributions (ISEE\_3D) as a plug-in for SPEDAS

Kunihiro Keika\*, Yoshizumi Miyoshi, Shinobu Machida, Akimasa Ieda, Kanako Seki, Tomoaki Hori, Yukinaga Miyashita, Masafumi Shoji, Iku Shinohara, Vassilis Angelopoulos, Jim W. Lewis and Aaron Flores

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## Abstract

This paper introduces ISEE\_3D, an interactive visualization tool for three-dimensional plasma velocity distribution functions, developed by the Institute for Space-Earth Environmental Research, Nagoya University, Japan. The tool provides a variety of methods to visualize the distribution function of space plasma: scatter, volume, and isosurface modes. The tool also has a wide range of functions, such as displaying magnetic field vectors and two-dimensional slices of distributions to facilitate extensive analysis. The coordinate transformation to the magnetic field coordinates is also implemented in the tool. The source codes of the tool are written as scripts of a widely used data analysis software language, Interactive Data Language, which has been widespread in the field of space physics and solar physics. The current version of the tool can be used for data files of the plasma distribution function from the Geotail satellite mission, which are publicly accessible through the Data Archives and Transmission System of the Institute of Space and Astronautical Science (ISAS)/Japan Aerospace Exploration Agency (JAXA). The tool is also available in the Space Physics Environment Data Analysis Software to visualize plasma data from the Magnetospheric Multiscale and the Time History of Events and Macroscale Interactions during Substorms missions. The tool is planned to be applied to data from other missions, such as Arase (ERG) and Van Allen Probes after replacing or adding data loading plug-ins. This visualization tool helps scientists understand the dynamics of space plasma better, particularly in the regions where the magnetohydrodynamic approximation is not valid, for example, the Earth's inner magnetosphere, magnetopause, bow shock, and plasma sheet.

**Keywords:** Velocity distributions of space plasma, In situ measurements of space plasma, Interactive visualization tool, The ERG project

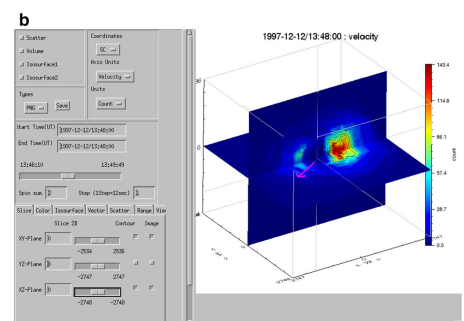


Fig. 5

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## The ERG Science Center

Yoshizumi Miyoshi\*, Tomoaki Hori, Masafumi Shoji, Mariko Teramoto, T. F. Chang, Tomonori Segawa, Norio Umemura, Shoya Matsuda, Satoshi Kurita, Kunihiro Keika, Yukinaga Miyashita, Kanako Seki, Yoshimasa Tanaka, Nozomu Nishitani, Satoshi Kasahara, Shoichiro Yokota, Ayako Matsuoka, Yoshiya Kasahara, Kazushi Asamura, Takeshi Takashima and Iku Shinohara

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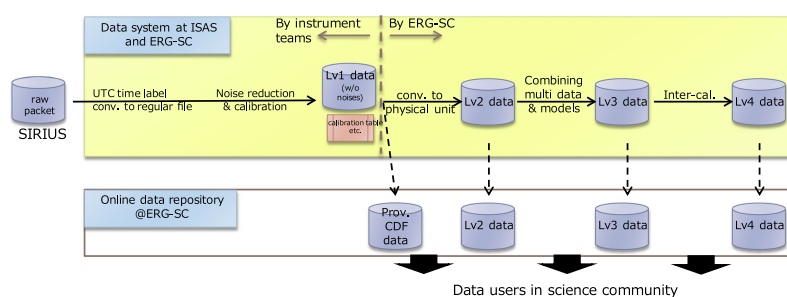
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### Abstract

The Exploration of energization and Radiation in Geospace (ERG) Science Center serves as a hub of the ERG project, providing data files in a common format and developing the space physics environment data analysis software and plug-ins for data analysis. The Science Center also develops observation plans for the ERG (Arase) satellite according to the science strategy of the project. Conjugate observations with other satellites and ground-based observations are also planned. These tasks contribute to the ERG project by achieving quick analysis and well-organized conjugate ERG satellite and ground-based observations.

### The ERG Science Center



The ERG Science Center serves as a hub of the ERG project.

The main tasks of the ERG-SC are

- 1) to archive and distribute data to both research teams and the public
- 2) to develop research software as SPEDAS plug-ins
- 3) to plan the operation of the ERG satellite and arrange for coordinated studies among ERG, other satellites, and ground-based observations.

Graphical abstract

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## OBITUARY

## Open Access

## In memory of Professor Takayuki Ono

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Professor Takayuki Ono of Graduate School of Science, Tohoku University, passed away on 21 December 2013. He was 63 years old. He was the Principal Investigator of the Geospace Exploration Mission: Exploration in energization and Radiation in Geospace (ERG) and played the leader of the ERG project. It is very unfortunate that he did not live long enough to witness the launch of the ERG (Arase) satellite on 20 December 2016 to which he had dedicated to so much of his life. His warm character appeared to everyone, and he had always encouraged young colleagues to realize the project.

Professor Ono was born on 5 August 1950. He graduated and received a Ph.D. from Tohoku University. He moved to National Institute of Polar Research in 1980. He came back to Tohoku University to take up the position of an associate professor and was promoted to a full professor in 2000. He is survived by his wife Naomi, four children, and five grandchildren.

Y. Miyoshi, T. Takashima, K. Asamura and I. Shinohara

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