# AN OVERVIEW AND INITIAL IN-ORBIT STATUS OF "INDEX" SATELLITE

Hirobumi Saito

Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency, Japan e-mail koubun@isas.jaxa.jp

Takahide Mizuno, Koji Tanaka, Yoshitsugu Sone, Seisuke Fukuda, Shin-ichiro Sakai, Nobukatsu Okuizumi, Makoto Mita, Yosuke Fukushima, Masafumi Hirahara<sup>\*</sup>, Kazushi Asamura, Takeshi Sakanoi<sup>\*\*</sup>, Akira Miura, Toshinori Ikenaga, and Yasunari Masumoto Japan Aerospace Exploration Agency, Japan <sup>\*</sup>Rikkyo University, Japan , <sup>\*\*</sup>Tohoku University, Japan

ABUSTRACT: INDEX ( REIMEI ) is a small satellite with 72kg mass, and is provided with three-axis attitude controlled capabilities for aurora observation. REIMEI was launched into a nearly sun synchronous polar orbit on Aug. 23<sup>rd</sup>, 2005 (UT) from Baikonur, Kazakhstan by Dnepr rocket. REIMEI satellite functions works satisfactorily in the orbit. Three axis control is achieved with accuracy of 0.05 deg. Multi-spectrum images of aurora are taken with 8Hz rate and 2 km spatial resolution and are being analyzed to investigate the aurora physics.

# INTRODUCTION

The Institute of Space and Astronautical Science, Japan Exploration Agency (ISAS/JAXA) has launched a series of scientific satellites including planetary spacecraft as well as astronomical observation satellites. Although the missions have achieved fruitful scientific results, these satellites cost nearly \$160 million including our own M-V launch vehicle and take longer than eight years to be developed. The launch frequency of the scientific satellites decreases significantly in this decay.

In addition to these "big, expensive, slow" missions, the authors plan to launch "small, inexpensive, fast" piggy-back satellites as good tools to demonstrate new technology and perform science observation. The piggy-back satellite INDEX (Innovative Technology Demonstration Experiment) has been developed since 2000<sup>1</sup>. INDEX was launched by Dnepr rocket in Aug. 23<sup>rd</sup> 21:10, 2005 UTC. After the launch INDEX was renamed REIMEI which means dawn in old Japanese word, celebrating the new era of small satellite with high performance in Japan. This paper describes the outline of the initial in-orbit results of INDEX, REIMEI.

# MISSION AND SYSTEM DESCRIPTION

# Aurora Observation

Auroral phenomena in the polar regions of the Earth, the Jupiter, etc, are characterized by auroral emissions of a wide wave length range, and energy and pitch-angle distributions of electrons and ions. A main scientific purpose of REIMEI satellite is an exploration to small-scale dynamics of terrestrial auroras, namely, their spatial distributions and time variations, and their correspondence to spectrum properties and spatial distributions of charged particles which generate the auroral emission <sup>1</sup>. One of observation instruments is a multi (three)-channel auroral camera (MAC) using three CCD imagers, and another is electron and ion energy spectrum analyzers (ESA/ISA) with top-hat type electrostatic optics.

# Demonstration of Advanced Satellite Technologies

The engineering mission is to demonstrate the advanced spacecraft technologies in orbit. The advanced technologies to be tested in REIMEI satellite are as follows:

three-axis attitude control system with 0.02 deg determination accuracy and 0.05 degree control

Size	$72  imes 62  imes 62  ext{ cm}^3$
Mass	72kg
Mission	Observation of Fine Structure of Aurora
	(Imager and Particle Analyzer)
	Engineering Technology Demonstration
	(7items)
Power	160W, Solar-Concentrated Solar Panels
	6.0AH Lithium Ion Battery
Attitude	Bias-Momentum Three-Axis Control
	Accuracy of 0.05 degree
Launch	Dnepr Rocket, 2005/8/24
Trajectry	Near Sun Synchronous
	$608 \times 655 \mathrm{km}$
Life	Longer Than Three Months

### Table 1 Outline of INDEX Satellite

accuracy in 70 kg satellite 2,3,4

- integrated satellite-control based on high-speed 32 bit RISC processor (SH-3, 60MIPS, 0.5W, triple voting system)<sup>1,5</sup>
- lithium ion rechargeable battery with laminate package as main battery system <sup>6</sup>
- solar-concentrated panel with thin film reflectors and high efficiency (27%) solar cells <sup>7,8</sup>
- variable emittance radiator with material of perovskite<sup>9</sup>
- Miniature GPS receiver modified based upon navigation GPS receivers <sup>10,11</sup>

## System Description



#### Fig.1 INDEX Satellite

INDEX is a small scientific satellite with size of 72 x  $62 \times 62$ (H) cm<sup>3</sup> and mass of 72 kg. REIMEI has two solar-concentrated deployable solar paddles with

power capability of 160W. Figure 1 is a photograph of REIMEI on ground. Table 1 describes the summary of REIMEI. The cost of REIMEI is about 4 million US dollars. The design, the integration and the test of REIMEI were performed by ISAS/JAXA staff. Common instruments such as battery, solar paddles were fabricated by the satellite manufacturing companies. The data handling instruments and power management instruments were fabricated by small venture companies. Many young staff and students were involved in the REIMEI development, working together with the venture companies. These development activities are very effective to activate space developments and space education.

INDEX satellite is controlled by the Integrated Controller Unit (ICU). ICU manages peripheral instruments including the sensors and the actuators. For sake of system compactness, there is no date bus outside of the ICU and all the instruments are controlled directly in the address space of the processor. Input/output ports are developed with space-qualified FPGAs.

The attitude control system of INDEX satellite is bias-momentum three-axis stabilized system <sup>2,3,4</sup>. The sensors for attitude control are a spin type sun sensor (SSAS), two-dimensional sun sensor (NSAS), a star tracker (STT), three-axis geomagnetic field aspect sensor (GAS) and three-axis fiber-optical gyroscopes (FOG). The attitude determination algorithm is based upon extended Karman filter, which estimates the bias rates of FOGs and the attitude of INDEX. The actuators of the attitude control are a small reaction wheel (RW) which provides the satellite with bias-momentum (0.5Nms), and three-axis magnetic torquers (MTQ).

The command link is S band communication with 1 kbps, and the telemetry link is S band with 131, 64, 32, 16, 8 kbps. The main control station of REIMEI is newly developed Sagamihara small satellite station with a 3 m antenna<sup>5</sup>.

## LAUNCH and TRACKING OPERATION

## Launch by Dnepr Rocket

In 2005 February, JAXA decided to launch INDEX as a piggy-back satellite for the OICETS (Optical inter-Satellite Communications Engineering Test Satellite) launch by Dnepr rocket from Baikonur Cosmodrome.

Three pyrolocks are used for INDEX fastening to the Dnepr rocket. At separation the pyrolocks release INDEX and then the third stage moves away from INDEX by the throttled back mode. The main attitude disturbance at the separation is plume effect with less than 7 deg/sec.It is very important for a piggy-back launch to simplify the rocket interface as much as possible. INDEX has no electrical I/F with the launch vehicle. This is possible because the onboard battery of INDEX is lithium-ion battery of which the self-discharge rate is very low. The final battery charging can be at 20 days prior to the launch.

# Launch Operation

The flight model transported from Japan to Baikonur through Moscow in the early July, 2005. The launch site operations were performed from July 12<sup>th</sup> by ISAS/JAXA staff and the graduate students. On Aug. 9<sup>th</sup>, the final battery charging was performed and then INDEX was installed on the Space Head Module of Dnepr rocket on Aug.11<sup>th</sup>.

INDEX was launched by Dnepr rocket from Baikonur at 2005 Aug.23, 21:09:58.8 UTC and separated from Dnepr at 21:25:17.6. The height of the apogee and the perigee are 654.866 km and 608.731 km, respectively. The orbit is nearly sun-synchronized orbit with the local time of about 12:00. INDEX turned on the electrical system automatically by means of its separation switches. INDEX started the sequence of the initial sun acquisition, which is described in "Initial Attitude Acquisition" section.

Kongsberg Satellite Services (KSAT) Svalsat ground station at Svarbard Island, Norway received the down link telemetry from INDEX for 13 minutes from 22:47 UTC. The received telemetry data was uploaded to the FTP site within 10 minutes from the receiving, which can be monitored from Japan through FTP.

INDEX firstly visited above Japanese ground stations six hours after the launch. The main station of INDEX for the launch phase, Uchinoura 20m antenna, received the telemetry signal at Aug.24, 3:10 UTC. The telemetry data indicate that INDEX is in spin motion of 1.0 rpm with sun angle of 44° and the solar paddles had been already deployed.

# Tracking Operation

Dairy operation of the REIMEI satellite is presently going on using the dedicated ground station at ISAS/JAXA Sagamihara campus[5]. The Sagamihara campus station has an antenna of 3 meter in diameter on the roof of the main building. If the onboard S-band transmitter (STX) is in the high-power mode, the bit rate of 131 kbps is available with the 3 meter antenna.

The REIMEI operation team consists of young researchers, engineers, and students. Most operation software and tools are developed by themselves and a venture software house, so that flexible operation becomes possible. For example, command plans and procedure documents can be automatically generated from the xml-based satellite operation procedure (sop) through script programs.

The operation team makes it a rule to check the commands generated from the sop using the prototype model of ICU (Integrated Control Unit) together with the dynamics simulator. This is because it is impossible to test all combination of software tasks running on the integrated computer before launch. The simulation environment can be easily connected to the ground station by coaxial switches.

In order to download scientific and engineering data, the Norwegian Svalbard Satellite Station (SvalSat) is complementarily utilized. The service is cost-effective because the acquired data are available via FTP in a few minutes from LOS.

#### SATELLITE PERFORMANCE IN ORBIT

#### Attitude Control

#### Initial Attitude Acquisition

Science INDEX has only one momentum wheel in one-axis and no thrusters, quick sun acquisition is impossible. Sun acquisition with slow rate is performed by magnetic torquers.

Figure 2 plots body sun angle versus time from separation. Libration dumping control is the first stage of initial sequence, and was finished at 1.9 hour as scheduled. The actual libration at separation was less than 0.05 rpm (0.3deg/sec), much less than the value of Dnepr specification (7deg/sec).

The second stage, spin-up control, was then started. On-board spin rate estimator, based on geomagnetic aspect sensor, terminated the spin-up control at 2.4 hour from separation, when nominal spin rate of 1.0 rpm was found to be achieved. Then sun acquisition control was started, with initial sun angle of 110 deg. The sun angle was reduced by the control law and at 5.6 hour, it reached to 60 deg. At this point, ACS automatically deployed the solar array paddle (SAP). SAP output power was balanced with power consumption at the sun angle of 40 deg, 6.0 hour from separation. Monte Carlo simulations predicted that this condition should be achieved within 11.1 hour, and the battery capability was designed to survive this duration. For the initial mission duration, primary batteries were used to enhance the survivability during the initial sun acquisition. Finally, the satellite acquires the stable sun-pointing attitude, with spin rate of 1.0 rpm. Only nutation dumping control is applied when sun angle decreased down to 8.0 deg, and once sun angle exceeded 13.0 deg, it is switched to sun acquisition mode again.

### Three Axis Control

In the initial checkout operation, the satellite-established sun pointing, three axis controlled attitude. The attitude feed controller was in the coarse-pointing mode, and had achieved +/-0.2 deg of accuracy. The residual magnetic torque, which is the interaction between the residual magnetic moment and the geomagnetic field, is the main disturbance torque for REIME. In order to improve the accuracy of three-axis control of REIME, on-board estimation of the residual magnetic moment seems to be effective  $^{2,3,4}$ . We developed the off-line observer of residual magnetic moment on the ground and tested it, comparing the flight data. The residual magnetic moment Mr was estimated with least square method, resulted in Mr=[-0.51, 0.042, 0.11] (Am2).

The estimated residual magnetic moment was uploaded to REIME via command. This value was used by REIMEI as a feedforward value, to cancel residual magnetic moment. This means that this Mr is subtracted from M, which is the output of magnetic torque control law. This is the fine-pointing mode for REIMEI three axis control.

Figure 3 shows the attitude error of three axes as functions of time. Since a momentum wheel is in the





z-axis, the attitude error of the z-axis is very small. The x-and y-axis control is performed based upon the above-mentioned fine-pointing control mode. The accuracies of x-and y-axis are improved to less that 0.05 deg. It is revealed that the Mr feedforward cancellation improves the pointing accuracy 2-4 times.

Fig. 4 Trend of Power Subsystem In REIMEI case, the estimation of the residual magnetic moment was carried out on ground as off-line calculation, however, online estimation will also practical with recursive least square method. Such real-time estimation will be valuable when residual magnetic moment varies dynamically, i.e., affected by solar cell current. Note that this residual magnetic moment observer should be also useful for a small or micro satellite with pure magnetic attitude control system.

### **Power Subsystem**

### Solar Array and Power Control

The Solar array of the INDEX satellite consists of 19 series- 10 parallel combination of the state-of-the-art



Fig. 4 Trend of Power Subsystem

triple junction solar cells mounted on a "dimpleless" honeycomb substrate, which was newly developed to enhance the rigidity of honeycomb panel. The bare cell efficiency is around 27 % which is the highest value in commercially available ones. The power generated by the solar array must be controlled to limit the maximum bus voltage of 35 V. The three stage sequential-partial-shunt system was adopted. The shunt transistors were placed across a portion of the solar array string allowing a better matching of the solar array power and the load demand. Trend of the power generated by solar array and the bus voltage are depicted in Fig. 4. Bus voltage was regulated lower than 35 V (Fig. 4(A)). Shunt currents are controlled adequately with currents of load and batteries as shown in Figs. 4 (B) and (C). Two lithium ion batteries with a total capacity of 6Ah were installed as a rechargeable secondary batteries that supplied electricity to the load during eclipse. Charge and discharge data are shown in Fig. 4 (C).

### Solar-Concentrated Paddle

Two rigid solar paddles with light weight reflectors were designed and installed on the satellite. Schematic drawing of the solar paddle was shown in Fig. 5. Polyimide thin film  $(25 \,\mu \text{ m})$  aluminized on the both sides was used as a reflector. Temperature of the reflector was designed to be  $130^{\circ}$ C which is higher than that of the solar cells (less than  $100^{\circ}$ C) in order to prevent contamination of the surface of the reflector and degradation of the power generation. When REIMEI flies form eclipse to sunlit, the secondary batteries require charging current as much as possible from the solar paddles. At the moment the current from the solar array achieves the maximum



Paddle

value without any shunt currents. Figure 4 (B) indicates the above-mentioned moment by a solid circle. The solar array with the reflector produced more than 160 W of electric power at temperatures around  $-20^{\circ}$ C. This generated power seems to be consistent with enhancement factor (about 1.2) of solar concentration as well as temperature dependence of the cell.

Figure6 is the SAP current as a function of the sun angle. When there is no solar concentration without the reflectors, the SAP current has cosine dependence on the sun angle as shown by the solid line in Fig.6. The solid circles indicate the measured SAP current for sun angle 0 deg as well as 25 deg. It is expected that the solar concentration vanishes at sun angle about 25 deg due to the reflection geometry. It is observed that the solar concentration effect appears at sun angle 0 deg by a factor 1.2. The measured value (silid circle) is in good coincidence with the predicted value by ground test (open circle).

#### **Battery**

We applied to REIMEI lithium -ion secondary battery based on pouch cells for the satellite. The cell is designed using manganese oxide for the positive electrode and graphite carbon for the negative. The rated capacity of the cell was 3.0 Ah. The electrolyte for the lithium-ion cell is dissolved by



Fig.6 Comparison of SAP Current between Predicted Value by Ground Test and Measured Value in Orbit. (bus voltage 29.0V, 90C) organic solvent, and packed by the Al-laminate film. Due to the configuration, the cell expands under the vacuum condition. This expansion increases the DC impedance of the cell. Furthermore, the leakage of the solvent through the adhesive area of the laminate films drastically loses the capacity of the cell/battery. Thus, the pouch cells were potted with resin and reinforced by the aluminum housing to enhance the tolerance against the vacuum environment in space. The energy density of the potted battery system is about 70W/kg.

We compare the flight data of the battery with the cycle test on ground in order to predict possible degradation of the battery in orbit. Figure 7 is long-term trends of the battery voltage at the end of eclipse for the flight data as well as the cycle test on ground. The ground test are performed for cell base as well as for a seven-series battery. The condition of the ground test is the case of the maximum load of possible consumption power in orbit. As a trend of the data, the flight data is in good coincidence with the ground cycle test. Some discrepancies are caused by the variation of satellite operation such as safe hold operation. We can predict the long-term performance of flight batteries in this method.

### Miniature GPS Receiver

We have developed the miniature GPS receivers based upon commercial GPS receivers for automobile navigation[10,11]. Satellites have higher velocities than 7km/sec, while GPS receivers on automobile are subject to earth rotation velocity less than 0.5 km/sec.



Fig. 7 Comparison between Flight Data of Battery Voltage at End of Eclipse and We modified commercial GPS receivers such that sweep frequency range is extended to cover the large Doppler frequency. The mass of the on-board GPS receiver is only 200g including the RF hybrid. The detailed performance evaluation by means of Spilent GPS simulator was carried out, indicating that the accuracy of positioning is about 15m including effects of ionosphere.

The first test of the GPS receiver was performed at 2005, Aug. 27<sup>th</sup>, 16:02:28 UTC. Without any predicted position data (cold start) the GPS receiver started 3 D positioning in 7 minutes and 10 seconds. Figure 8 describes the number of NAVSTAR satellites that the GPS receiver lock in the initial acquisition process. The time to first fix (TTFF) in the case 7 minutes and 10seconds. This TTFF seems to be shoter than the one that is expected from the GPS simulation. Then the GPS receiver keeps tracking more than seven NAVSTAR satellites with PDOP less than 2.2. The orbit determination test was performed by GPS data. Figure 9 is a variation of the raw GPS positioning data, which is the difference between the GPS positioning result and the position from the orbit determination by means of the GPS data. The random noise of the GPS receiver for one minute is observed to be about 0.5m. This random noise is qualitatively consistent with the GPS simulation on ground <sup>10</sup>.



Fig. 8 Num ber of Aquired NAVSTAR Satellite at Initial GPS Acquisition as Function of Time

#### Auroral Observation

#### Auroral Camera

The science instruments on Reimei have been obtaining high-quality data with several observation modes since all of instruments were successfully turned on as initial operations on orbit at the end of October, 2005. We, here, present observational results with two types of observation modes, one of which is the auroral image-particle simultaneous observation mode (Mode-S). Another mode is the auroral height distribution measurement mode (Mode-H).

In Mode-S, obtains 64x64-pixel two-dimensional auroral images at three wavelengths of 428, 558, and 670 nm at every 120 msec with an multi(three)-channel monochromatic auroral imaging camera (MAC). Also Reimei obtains energy-pitch angle distribution functions of auroral particles with the energies of 12 eV to 12 keV for electrons and 10 eV to 12 keV for ions at every 20 msec with electron/ion energy spectrum analyzers (ESA/ISA). The most noticeable property of Mode-S is that the field-of-view of MAC catches the Reimei footprint mapped onto the aurural altitude of 110 km along the local field line on which Reimei is located. The precise on-board control of the Reimei attitude is performed of the pre-calculations based on the geomagnetic field model and the predicted Reimei attitude. The Mode-S realizes the simultaneous observations of two-dimensional distributions of auroral emissions for three typical wavelengths with the precipitating electrons causing the auroral emissions with high-time and -spatial resolutions. These resolutions have not been attained ever in any



Fig.9 Variation of GPS Positioning

previous satellite missions.

Figure 10 shows an example of the Mode-S observations carried on December 26, 2005 at the Reimei altitude (about 620 km) in the mid-night auroral region. In the electron energy-time spectrograms of three pitch angle ranges, a clear structure of the accelerated electrons is seen from 09:10:44 to 09:11:00 UT, in which the maximum energy of electrons is almost corresponding to the uppermost range of ESA. The precipitating component of electrons plotted in the uppermost panel has the largest energy fluxes in the three pitch angle ranges. This kind of the accelerated electron structure in the downward (earthward) direction is a so-called inverted-V, which has been observed also in a number of previous satellite missions exploring the polar magnetosphere. On one hand, Reimei-MAC can take the successive and simultaneous auroral images caused by these precipitating electrons accelerated in the inverted-V phenomenon. The example presented in Fig. 10 suggests that there are several intense and rapidly changing auroral arcs even in one clear electron inverted-V structure. The further advanced data analyses would enable us to compare the electron energy fluxes into the auroral altitude with the highly structured auroral emissions.

The next examples are from the Mode-H observations. In Mode-H, the satellite rotates around the axis almost parallel to the sunward direction in order to direct the FOV of MAC toward the limb of the Earth. The aim of this mode is to observe auroral height distributions and resonance fluorescence/scattering of outflowing ionospheric ions along the field-line in the sunlit region. From the geometry of observation, MAC obtains auroral images of ~270x270 km in horizontal and vertical directions, respectively, at a distance of 2000 km from the satellite with spatial and time resolutions of ~4x4 km and 1 sec, respectively.

Figure 11 shows examples of Mode-H observations performed at the beginning of December 2006 by



UT=09:10:44.82 UT=09:10:47.70 UT=09:10:50.57 UT=09:10:53:45 UT=09:10:56:32 UT=09:10:59:32 UT=09:11:02:20

Figure 10. An example of simultaneous observation of auroral images and particles using Reimei-MAC and ESA. The three top panels show the energy (vertical axis) and observational time (horizontal axis) spectrograms sorted into three pitch angle ranges (0<P.A.<60, 60<P.A.<120, 120<P.A.<180) of electrons from 12 eV to 12 keV measured by ESA. The electron energy fluxes are plotted by a color code. The lower three types of square plots with blue, green, and red are auroral images taken by MAC. A dot in each image indicates the footprint of Reimei mapped onto the ionospheric altitude of 110 km along the local field line on which Reimei is located at each of exposure time shown at the bottom.

Reimei-MAC. It is found that emissions are clearly detected in 428 and 670 nm images above the shadow of the Earth seen in the bottom. Further, the weak emission is also obtained in 558 nm image. Since these emissions occurred in the sunlit region, these are probably resonance fluorescence/scattering. Note that the filter transmission bandwidth of MAC channel: the full-width half maximum of 428, 558, 670 nm channels are 2.5, 1.6, and 38.2 nm, respectively. Thus, if emission is continuum, the strongest intensity is obtained in 670 nm image.

It is suggested that 428 nm emission should be the first negative band of molecular nitrogen ion existing in the topside ionosphere. On the other hand, the candidates of 558 and 670 nm emissions are OI green line and first positive band of molecular nitrogen, respectively. However, especially in the case of molecular nitrogen, it is difficult to uplift these neutral particles to these altitude ranges. Since the



Figure 11. Examples of limb observations of resonance fluorescence using Reimei-MAC at the beginning of December 2006. In each case, 428, 558, 670 nm images are displayed from top to bottom, and each image rotates so that the earthward direction corresponds to the bottom side, and the sunward direction is the left hand side. The altitude range of each image is roughly from 400 to 600 km. The dark area in the bottom of each image is the shadow of the Earth.

filter bandwidth is wide on the 670 nm image, it would be possible to detect other emissions of different ions, atoms or molecules. However, the appropriate emission sources for 558 and 670 images can not be found at this moment.

## CONCLUSION

REIMEI is a small scientific satellite for aurora observation and advanced satellite technologies, and was launched into a nearly sun synchronous polar orbit on Aug. 23<sup>rd</sup>, 2005 (UTC) from Baikonur, Kazakhstan by Dnepr rocket. REIMEI satellite functions work satisfactorily in the orbit. The three-axis attitude control is achieved with accuracy of 0.05deg. REIMEI is performing the simultaneous observation of aurora images as well as particle measurements . REIMEI indicates that even a small satellite launched as a piggy-back can successfully perform the unique scientific mission purposes.

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