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DEVELOPMENT OF THE MULTI-SPECTRAL AURORAL CAMERA ONBOARD THE INDEX SATELLITE

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ABSTRACT

To investigate the fine-scale auroral structures, high time and spatial resolution imaging observations of optical auroras will be made by a multi-spectral auroral camera (MAC) onboard the INDEX satellite which will be launched by an H2A rocket as a piggyback satellite into a polar orbit at an altitude of ~700 km. Monochromatic auroral image data at emissions of N_2^+ first negative band (427.8 nm), OI (557.7 nm), and N_2 first positive band (670 nm) are obtained by MAC with the field-of-view (FOV) of 7.6° using three independent CCD cameras in combination with interference filters. MAC will operate in the nightside auroral region by two operation modes in the following. (1) Simultaneous measurement with particle sensors (ESA/ISA). In this mode, MAC observes an imaging area of ~80x80 km (at a 100 km altitude) around a magnetic footprint with spatial and time resolutions of ~1.2 km and 120 msec, respectively. (2) Auroral height distribution measurement. The attitude of INDEX satellite is changed to direct the FOV of MAC on the limb of the Earth. In this mode, MAC observes an imaging area of ~270x270 km (at a 2000 km distance from the satellite) with spatial and time resolutions of ~4 km and 1 sec, respectively. In this paper, the science mission, the instrumentation, and observation modes concerning on MAC will be presented.

INTRODUCTION

The mid-altitude auroral acceleration region has been investigated with immense interest over three decades. From in situ measurement data obtained by satellites and rockets, it is found that the energy spectra of precipitating electrons are characterized by a monoenergetic beam of 1–10 keV. The formation of monoenergetic downward electrons is interpreted by the existence of the quasi-static field-aligned potential drop. The characteristics of the field-aligned acceleration event have been examined theoretically (e.g. Chiu and Schulz, 1978) and observationally (e.g., Reiff et al., 1988). Since the field-aligned current intensity is linearly proportional to the potential drop (Knight, 1973), it is clear that the existence of the acceleration region plays important role on the magnetosphere-ionosphere coupling system (Lyons et al., 1979, Weimer et al., 1987, Lu et al., 1991, Sakanoi et al., 1995).

Recently, Freja and FAST revealed fine-scale structures of particles, field-aligned currents, electric fields and waves (e.g., Marklund et al., 1997, Carlson et al., 1998, Ergun, 1999). Since the fine-scale acceleration region certainly corresponds to optical auroral structure in the polar region, conjugate observations between satellites and ground-based all-sky imagers have been made so far and showed the auroral arc thickness in a range between two to several tens of kilometers (Stenbaek-Nielsen et al, 1998, Hallinan et al, 2001). On the other hand, the typical auroral thickness obtained by ground-based photometers is found to be about 100 m (Borovsky, 1993). Since the formation of those fine-scale acceleration region could not be explained only by the quasi-electrostatic potential drop, it is suggested that additional acceleration processes, such as the inertial Alfvén waves, should be needed (Knudsen, 2001, Swift, 2001). Thus, the additional acceleration processes are essential to produce auroral fine structures. However, the examination on the relationship between the fine structure of auroral particles and that of auroral emission is insufficient since there are not many chances of simultaneous measurement between a satellite

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and a ground-based instrument. Further, especially for a panchromatic imager which has been commonly operated, a ground-based all-sky imager have disadvantages to observe auroral fine structures since the estimated auroral structure would be degraded due to the overlapping of emission layers in the line-of-sight direction called the van Rhijn effect. Also, it is difficult to determine the quantitative physical parameters from panchromatic image data. Auroral observations with an optical instrument onboard a satellite would overcome these difficulties, and auroral image data have been obtained from space mainly in the ultra-violet wavelength range. However, in general those auroral images have been obtained at high altitudes (~several ten thousands kilometers) to monitor a global distribution of aurora. Thus, the auroral fine structures could not be derived from those satellite data due to the orbital properties and the limitation of instrumental resolution.

INnovative technology Demonstration EXperiment (INDEX) is the first Japanese micro-satellite mission selected by Institute of Space and Astronautical Science (ISAS) to archive the specific investigations of fine auroral structures and some advanced engineering subjects. The INDEX satellite will be launched by an H2A rocket in 2004 as a piggyback payload into a sun-synchronous orbit at a 700-km altitude in the meridian of 1030–2230 LT (Saito et al., 2001). Three scientific instruments will be carried by the INDEX satellite as described in the following. One is the multi-spectral auroral camera (MAC) which has three channels of CCD in combination with interference filters for obtaining monochromatic images of visible auroras. The second is the low-energy auroral particle instrument consisting of two top-hat type sensors: electron and ion energy spectrum analyzers (ESA/ISA) (Asamura et al, 2003). The other is the electric current monitor (CRM), based on the detection principle of a Langmuir probe. In this paper, our novel scientific mission, an instrumental specification, and several observational modes of MAC are presented.

SCIENTIFIC OBJECTIVES

The most important scientific purpose of the INDEX satellite mission is the observations performed with the high time and spatial resolutions of auroral emissions, particles, and plasma environment for clarifying the fine scale structures of auroral acceleration region. The INDEX satellite will be entered into a sun-synchronous circular orbit with the inclination of 98.6 degrees in the meridian of 1030–2230 LT at a 700-km altitude. The attitude of the INDEX satellite is a bias-momentum three-axis stabilized with a reaction wheel in combination of two magnetic torqueres. According to the low-altitude orbit covering the nightside auroral oval and the three-axis attitude control system, we will be able to make a unique observation of fine structures of auroral emission using the multi-spectral auroral camera (MAC). The major scientific objectives of INDEX MAC experiment are summarized as follows.

1) Fine structures of auroral emission and their relationship to precipitating particles

When the field-of-view (FOV) of MAC coincides with a geomagnetic footprint on which the satellite is located, the simultaneous measurement between auroral images by MAC and particles by ESA/ISA can be carried out with the high time and spatial resolutions. Thus, the causal relationship between precipitating particles and auroral emission is clarified in detail with regard to various types of auroral emission structures, such as arcs, patches and rays. Further, the spatial relationship between ion outflows and auroral emission is revealed. The configuration of observation is presented later in detail.

2) Total and characteristic energies of precipitating electrons

The MAC experiment is characterized by the monochromatic imaging at three auroral emissions of OI green line (557.7 nm), N_2^+ first negative band (427.8 nm) and N_2 first positive band (670 nm). From the ratio of emission intensities, the characteristic energy of precipitating electron can be deduced (e.g., Rees and Luckey, 1974). In addition, from the intensity of N_2^+ first negative band, the total energy of precipitating electrons can be inferred (e.g., Ono and Morishima, 1994). The advantages of the MAC experiment are that it is possible to validate those parameters using in situ particle data by ESA/ISA, and that there is no atmospheric absorption which degrades the absolute intensity of aurora.

3) Auroral height distributions

By controlling the satellite attitude to direct the FOV of MAC toward the limb of the Earth, the auroral height distributions can be measured with high time and spatial resolutions. The detailed properties of the observation are described later. The auroral stereoscopic examination would be made using the coordinated measurement data obtained with MAC and ground-based instruments such as an IS radar and an all-sky imager.

4) Temporal variation of aurora

The highest time and spatial resolutions of MAC is 120 ms (8.3 images/s) and 1.2 km, respectively. These high time and spatial resolution imaging data enable us to study the temporal variation of auroral structures, such as pulsating and fast moving auroras.

INSTRUMENT DESCRIPTION

Specifications of the Multi-spectral Auroral Camera

The multi-spectral auroral camera (MAC) instrument onboard the INDEX satellite is designed to make auroral imaging observations with high time and spatial resolutions at three different wavelengths. Figure 1 illustrates the sectional view of the MAC instrument installed on the satellite. MAC has three channels though one channel is schematically presented in Figure1. Each channel has an interference filter, objective lenses, and a CCD chip which is cooled by a thermal path using graphite sheets connected to a radiator. MAC also includes the electric boards to conduct digital and analog data processing and provide clock signals driving CCDs. As shown in Figure 1, MAC is installed on the satellite in such a way that the direction of field-of-view is 45° slanted with respect to the surface of satellite panel. This slant angle is selected to observe the auroral emission at the magnetic foot point in the nightside auroral oval. Three hoods are exposed to the outside of satellite through three ellipse-shaped openings of the satellite panel.

Table 1 shows a summary of instrumental parameters of MAC. At the forefront of each channel, a synthetic silica plate is placed to block radiation. Three interference filters, whose center wavelengths are 428.2, 558.0, 671.7 nm are used to observe the auroral emissions of N_2^+ first negative band, OI 557.7 nm, N_2 first positive band, respectively. The objective lenses are also made of fused silica for blocking radiation. The focal length and F-number of the objective lenses are 50 mm and 1.7, respectively. CCD is the interline type with pixels of 1024×1024. As described later in detail, the 16×16-pixel binning is mainly used for auroral observations, while the 2×2-pixel binning is used for calibrations. This CCD is characterized by the high sensitivity and the low noise since the quantum efficiency is ~0.6 at 557.7 nm and the sum of dark and read out noises is measured to be typically 0.3 r.

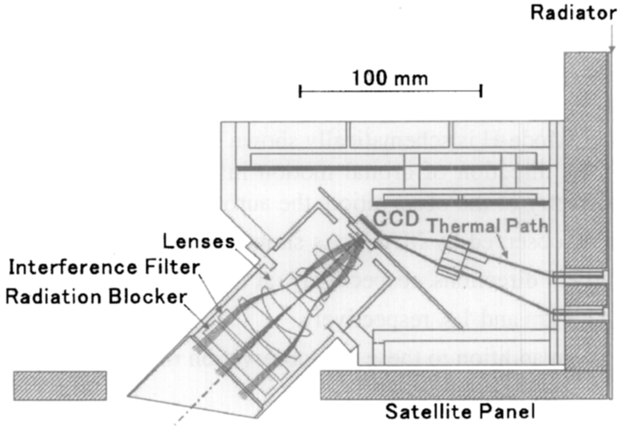

Fig. 1. Sectional view of the multi-spectral auroral camera (MAC) onboard the INDEX satellite.

Table1. Summary of the instrumental parameters of MAC

Apparatus	Parameter and value		
Radiation blocker	material: synthetic silica, diameter: 50 mm, thickness: 10 mm		
Interference Filters	center (nm)	FWHM[*1] (nm)	peak transmittance
N_2^+ first negative	428.2	2.47	0.46
OI 557.7 nm	558.0	1.68	0.56
N_2 first positive	671.7	35.95	0.97
Objective lenses	material: fused silica, f=50 mm, F=2.0, field-of-view: 7.6°		
CCD	type: interline, pixels: 1024x1024, pixel size: 6.45x6.45 μm binning: 2x2, 8x8, 16x16 pixels (selectable) efficiency: 0.6 (at 557.7 nm), noises: ~0.3 r.m.s. cts (at 0°C)		
Cooling of CCD	Thermal path using graphite sheets connected to the radiator		
Weight	4.5 kg[*2]		
Power	11 W (1 ch. on), 13 W (2 ch. on), 15 W (3 ch. on)		

[*1] FWHM indicates the full width of half maximum.
[*2] To be revised.

m. s. counts per pixel at 0°C from operational tests discussed later. CCD is cooled below 0°C by the thermal path using twenty sheets of carbon graphite. Sensitivity estimations are presented later.

Observation Modes

Although there are several observation modes on the operations of scientific instruments onboard the INDEX satellite, in this section two modes are mainly described concerning on the observation with MAC. One is the image and particle simultaneous measurement mode (Mode-S), and the other is the auroral height distribution measurement mode (Mode-H). Figure 2 shows the schematic drawings of the observation modes of MAC. Further, the characteristics of observation modes is summarized in Table 1. In both modes, the 16×16-pixel binning of CCD is performed taking a compromise among fast exposure time, sufficient sensitivity for weak auroral intensity, satellite motion during an exposure, data processing speed, and capacity of satellite system memory into account. Since CCD has 1024×1024 pixels and the 16x16-pixel binning is made, the CCD area is divided into 64×64 bins.

Mode-S is schematically shown in Figure 2a. In this mode the satellite attitude is controlled to obtain the full pitch-angle distribution of auroral particles with ESA/ISA by tracking the geomagnetic field orientation, and also controlled to direct the FOV of MAC to the geomagnetic footprint. Under the best situation, auroral images and corresponding auroral particles are simultaneously measured by MAC and ESA/ISA, respectively. Such situation is expected to occur in a winter season at the northern hemisphere. As shown in Table 1, MAC obtains auroral images of ~80×80 km area at a 100 km altitude with a spatial resolution of ~1.2×1.2 km and a time resolution of 120 msec. On the other hand, ESA and ISA observe the energy and pitch angle distributions of 10eV/q–12 keV/q electrons and ions, respectively, with a time resolution of 20 ms.

Mode-H is schematically shown in Figure 2b. In this mode, the satellite rotates around the axis almost parallel to the direction of orbital motion in order to direct the FOV of MAC toward the limb of the Earth. From the geometry of the observation, the auroral height distribution at a distance of 2000 km from the satellite is expected to be observed by MAC. As shown in Table 1, MAC obtains auroral images of ~270×270 km in horizontal and vertical directions, respectively, at a distance of 2000 km from the satellite with a spatial and time resolutions of ~4×4 km and 1 s, respectively.

In addition to these two observation modes, there are other modes on the MAC operation described briefly in

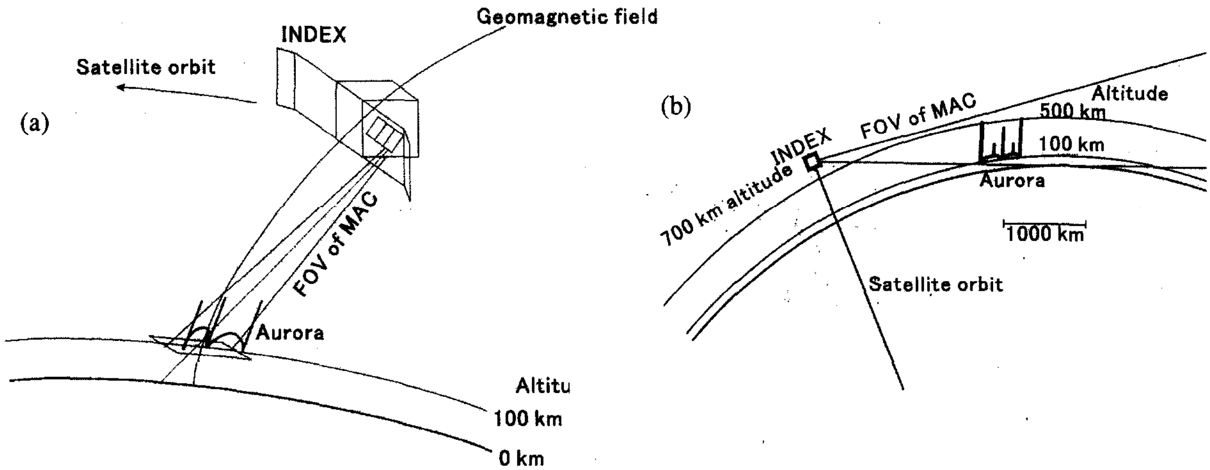

Fig. 2. Schematic drawing of the observation modes of MAC. (a) Image and particle simultaneous measurement mode (Mode-S). (b) Auroral height distribution measurement mode (Mode-H).

Table 2. Summary of auroral observation modes by MAC.

	Spatial resolution	One image area size	Exposure cycle
Mode-S (Image/particle simultaneous measurement)	1.2 x 1.2 km at a 100 km altitude	80 x 80 km at a 100 km altitude	120 msec.exposure: 40msec, pause 80 msec.
Mode-H (Auroral height distribution measurement)	4 x 4 km at a 2000 km distance from the satellite	270 x 270 km at a 2000 km distance from the satellite	1 sec (exposure: 480msec, pause 520 msec)

the following. One is the image calibration mode (Mode-C) for image data calibration, that is, the determination of absolute sensitivities and the direction of FOV, by obtaining the land structure on the ground or stars. The CCD binning is 2×2-pixel, namely, the CCD area is divided into 512×512 bins, and the exposure cycle is 4040 ms. The other is the high/low imaging mode (Mode I(H/L)). With this mode ESA/ISA is turned off and only MAC is operated. Mode-I(H) is also used for the observation of auroral height distribution with a higher resolution compared to Mode-H. In this mode, the CCD binning is 8×8-pixel, namely, the CCD area is divided into 128×128 bins, and the exposure cycle is 480 ms. On the other hand, Mode-I(L) is similar to Mode-S except that ESA/ISA is not operated. In this mode, the CCD binning is 16×16-pixel, and the exposure cycle is 120 ms or 1 s.

Data Handling and Sensitivities

Image data accumulated on CCD are initially digitised by the A/D conversion unit of MAC into a 12-bit form with a linear scale. These digital data are transferred into the Science data Handling Unit (SHU) onboard the satellite which control MAC, ESA/ISA and CRM and process scientific data. MAC data are then compressed into 8-bit form by SHU. At a present status, this data compressing is made with the simple bit shift method. The appropriate level of bit shift is chosen for each combination of the channel and the observation mode since CCD counts are variable depending on the wavelength of auroral emission and the exposure time.

The counts at each pixel obtained by MAC is calculated from the equation

$$N = I\,(10^6/4\pi)\,A\,\Omega\,T\eta\,t\,F, \tag{1}$$

where N is the counts at each pixel, I is the auroral intensity in Rayleigh, A is the optical aperture, Ω is the solid angle subtended by a single pixel, T is the optical transmission, η is the quantum efficiency of CCD, t is the exposure time, and F is the factor of the 12-bit A/D conversion. Using Eq. (1), the sensitivities of MAC are determined on each combination of the channel and the observation mode. Finally, in the case of Mode-S, the maximum auroral intensity and the resolution measured by MAC are set to be 74 kilo-Rayleigh and 370 Rayleigh/bit, respectively, on each channel after the 8-bit data compress. Similarly, in the case of Mode-H, the maximum auroral intensity and the resolution are set to be 61 kilo-Rayleigh and 123 Rayleigh/bit, respectively. These sensitivity values are tentative and will be determined by the calibration test scheduled in the spring of 2003.

OPERATIONAL TESTS

Various tests of the MAC instrument including the integration with the bus system of the satellite, mechanical tests, and thermal vacuum tests are now in progress. The functions of MAC have been checked with SHU and a command simulator at the laboratory of ISAS. So far, we have fixed operational problems of MAC, and confirmed that the MAC can be correctly operated on each combination of the channel and the observation mode. We also measured the noise properties and the offset in the CCD counts by setting MAC into a temperature-controlled vacuum chamber. As a result, we obtained that the total noises are ~2.5, 2.9, 3.0 r. m. s. counts per pixel on the 2x2, 8×8, 16×16-pixel binning, respectively when CCD is cooled below 0°C. Since these noises corresponds to an auroral intensity of ~1kR, auroral intensities can be precisely determined by MAC. On the other hand, the offsets increase with increasing temperature and found to be ~33, 77, 90 counts per pixel on the 2×2, 8×8, 16×16-pixel binning, respectively. Under the stable temperature conditions, these offset values are nearly constant and can be subtracted exactly in the data processing.

CONCLUDING REMARKS

The multi-spectral auroral camera (MAC) onboard the INDEX satellite will provide high time and spatial resolution imaging data of auroral structures at three emissions of N_2^+ first negative band (427.8 nm), OI (557.7 nm), and N_2 first positive band (670 nm). MAC will be operated with two observation modes in the following. (1) Mode-S: Image/particle simultaneous measurement mode. In this mode, MAC observes an imaging area of ~80×80 km (at an 100-km altitude) around a magnetic footprint with the spatial and time resolutions of ~1.2 km and 120 ms, respectively. (2) Mode-H: auroral height distribution measurement. In this mode, MAC observes auroral distributions in the direction of the Earth's limb an imaging area of ~270×270 km (at a distance of 2000 km from the satellite) with the spatial and time resolutions of ~4 km and 1 s, respectively. Various tests of the MAC instrument including the integration with the bus system of the satellite are now in progress. It is found from the operational tests of MAC that the CCD noises are less than ~3 r. m. s. counts per pixel on each observation mode when CCD is cooled below 0°C, which corresponds to the error of an auroral intensity of ~1kR. These precise auroral image data combined with the simultaneous particle data will enable us to make unique investigations of fine scale auroral structures.

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