Attitude Control Systems for Imaging the Moonlit Ground: Development and On-orbit Updating Results of CE-SAT-IIB

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ABSTRACT

Canon Electronics Inc. (CEI) is developing optical micro satellites “CE-SAT” for demonstrating in-house attitude determination and control systems (ADCS) and optical systems in order to achieve high-resolution and high-sensitivity imaging. CEI is now operating two satellites on orbit. The second satellite CE-SAT-IIB has the ability to take images of the ground surface with 5m GSD in the night using an Ultra High Sensitivity Camera (UHSC) and a highly accurate ADCS. The satellite has ability to track the ground with 20 arcsec/s or better of pointing stability, and this makes 100 milliseconds or longer exposure time possible. As the result, the satellite can get images of the moonlit ground surface clearly. To realize such high stability of pointing, CEI developed most components for ADCS in-house and updated software of the satellite and components on orbit. Now CE-SAT-IIB can get the ground images with 1800 milliseconds exposure time and get color images of night deserts like imaging in daylight. Additionally, this ADCS enables the satellite to get various images of the ground with changing area, sensitivity, and temporal resolution of imaging by selecting a target of pointing, exposure time, and imaging interval. Furthermore, high-speed moving objects including satellites and space debris can be photographed utilizing the high sensitivity of the UHSC.

SATELLITES DEVELOPMENT OF CANON ELECTRONICS

Canon Electronics Inc. (CEI) started a business in space industry in 2009, and CEI is developing optical micro satellites with utilizing the technology and expertise in precision machines and optics of Canon group. CEI launched its first satellite in 2017 and CEI is now operating two satellites on orbit. The second satellite, CE-SAT-IIB, demonstrates in-house attitude determination and control systems (ADCS) and optical systems[1]. After successful operation of CE-SAT-IIB, CEI has started accepting orders for micro-satellite busses and satellite components in 2021.

In-house Development and Operation

CEI has developed most components for ADCS, satellite bus systems, and optical systems in-house. This made it possible to develop optical micro satellites for high resolution and high sensitivity imaging with high accuracy of attitude control. And, CEI is continuously updating these components and satellite systems utilizing results of on-orbit operations and experiments.

Various Imaging with Area Sensors and Attitude Control

Detectors of CE-SAT are area sensors that developed based on cameras of Canon. With these cameras and ADCS, CE-SAT can get images or even movies of the ground with tracking target points on the ground surface or center of the earth. This means it is possible to change area, sensitivity, and temporal resolution of imaging by selecting target of tracking, exposure time, and imaging interval. Additionally, CE-SAT can get images of not only ground surface, but also stars and high-speed moving objects like satellites with inertial pointing.

MOONLIT GROUND IMAGING

Previously, the main target of night imaging with optical satellites was observation of artificial lights[2,3], and some satellites[4-8] have the ability to image night urban areas. However, imaging moonlit ground was still difficult even with these satellites.

Figure 1: Night image of Salt Lake airport

Moonlit imaging with optical satellites will widen the usage of satellite imaging. Figure 1 shows a sample night image of Salt Lake Airport taken by CE-SAT-IIB. Here we can see not only roads or buildings luminated by streetlights, but also moonlit runways or ground around airport without any artificial lights. With this imaging sensitivity of CE-SAT-IIB, it is also possible to image moonlit forests and deserts. In other words, moonlit ground images reveal both the human activity and the night state of the earth as it is.

On the other hand, the luminance of moonlit ground is one in ten-thousandth or less of sunlit ground. Thus, moonlit imaging requires quite higher sensitivity of the camera and longer exposure time than daylight imaging.

Performance of Ultra-High Sensitivity Camera

CEI is developing the Ultra-High Sensitivity Camera (UHSC) for optical satellites and the sensitivity of this camera is up to 4,000,000 (ISO equivalent). This means the UHSC is capable of imaging moonlit ground without any artificial lights when the exposure time is 100 ms or longer.

Requirements of Attitude control

Besides, high accuracy and stability of attitude control are also required. For getting clear images of moonlit ground, satellites need to track the ground with high pointing stability during exposure time in order to prevent "camera shake". For example, 20 arcsec/s or better pointing stability is needed for getting images of moonlit ground with 5 m GSD from 500 km altitude. This is a big challenge for attitude control. And the higher pointing stability the satellite has, the longer exposure time can be available and the darker the ground surface can be photographed. In order to achieve such high stability of pointing, CEI developed highly accurate sensors and actuators in-house. This made it possible to develop ADCS of the satellite by bringing out the performance of these components and update the software of them on-orbit.

ABOUT CE-SAT-IIB

CE-SAT-IIB was designed to achieve various imaging including moonlit imaging with the UHSC and in-house developed ADCS. Figure 2 shows a picture of CE-SAT-IIB flight model, and general specifications are shown in Table 1.

Figure 2: CE-SAT-IIB flight model

Table 1: CE-SAT-IIB general specifications

Parameter	Value
Dimensions	292 x 392 x 673[mm]
Mass	35.5[kg]
Power generation	average 40[W]
Communication	Up: 32[kbps] in S band Down: 0.5/8.7[Mbps] in X band and 150[Mbps] for test
Attitude control	Three axis zero momentum
Orbit	Sun-synchronous Altitude: 500 km
Camera	Main: UHSC + 200 mm telescope Sub: EOS M100 + 87 mm telescope

Camera and Telescope Specifications

CE-SAT-IIB has three cameras, and the main camera unit consists of the UHSC and 200 mm Cassegrain telescope. Table 2 shows the specifications of the CE-SAT-IIB main camera unit.

Table 2: Main camera unit specifications

Parameter	Value
Sensitivity	Up to 4,000,000 (ISO equivalent)
Resolution	5.1[mGSD]
Wave length	400-700[nm]
Main mirror diameter	200[mm]
Focal length	1860[mm]
Image foot print	3.5 x 2.3[km]
Telescope type	Cassegrain + correction lens
Shutter speed	1/8000 – 1.8[sec]
ND filters	ND16 and ND63 (detachable)

The sensitivity of the UHSC is up to 4,000,000 (ISO equivalent). This high sensitivity makes it possible to image moonlit ground. In addition, this unit is capable of imaging both sunlit and moonlit ground by only changing the sensitivity and ND filter settings of the UHSC.

ATTITUDE DETERMINATION AND CONTROLL SYSTEM OF CE-SAT-IIB

In order to achieve high stability of ground tracking and various imaging, CEI developed ADCS of CE-SAT-IIB with the following strategies.

1. Use highly accurate Star Trackers (STT) and Gyro sensors to determine the attitude of the satellite with arcsec order accuracy.

2. Calculate target attitude on-board at every control torque calculation.

3. Change the control method and adjust control parameters depending on the target of pointing in order to achieve various imaging.

4. Use Reaction Wheels (RW) with small disturbance and short output delay.

It is also important to design structure, communication system, and power system with minimizing constraints on the satellite attitude.

Details of ADCS of CE-SAT-IIB are shown below.

In-house Components for Attitude Determination and Control System

CEI has developed most ADCS components. Particularly, STT, Inertial Reference Unit (IRU), and RW are key components for achieving high stability of ground tracking. The appearances of these components are shown in Figure 3-Figure 5 and specifications are summarized in Table 3-Table 5.

Figure 3: STT

Table 3: STT specifications

Parameter	Value
Dimensions	60 x 60 x 134[mm]
Mass	400[g] (including baffle)
Field of view	13[deg]
Accuracy	Cross-boresight 7[arcsec] (3σ)
Slew rate	>1[deg/s]

Figure 4: IRU

Table 4: IRU specifications

Parameter	Value
Dimensions	138 x 116 x 90[mm]
Mass	< 1400[g]
Range	5[deg/s]
Bias RUN stability	< 0.3[deg/h]
Bias ON-OFF stability	< 0.5[deg/h]
Allan Variance	< 0.5[deg/h] @ averaging time 1sec
Output	Integrated value of 3-axis angular velocity and Integrated time

Figure 5: RW

Table 5: RW specifications

Parameter	Value
Dimensions	50 x 50 x 38[mm]
Mass	277[g]
Moment of inertia	5.85 x 10^{-5}[kgm^2]
Total momentum storage	0.0214[Nms]
Torque range	5[mN]

To achieve the high stability of pointing during ground tracking, measurement accuracy of angular velocity is the most important. IRU is consist of two mechanical gyro scopes and the bias stability of it is better than 0.3

deg/h. It is noteworthy that, Allan variance of it is smaller than 0.5 deg/h at 1 second of averaging time. This means, noise of output is so small that IRU can measure angular velocity with 1 arcsec/s accuracy.

The attitude accuracy of STT output is better than 7 arcsec (3σ) in cross-boresight. This is accurate enough to determine satellite attitude and estimate the bias of angular velocity measured by IRU.

RW is very small and light, but it has enough momentum storage to rotate the satellite during ground tracking. In addition, jitter disturbance is small and it can generate torque as a command precisely. Output response of RW is very high and this is suitable for rapid and precise attitude control.

Attitude Determination

CE-SAT-IIB determines its attitude accurately using extended Kalman filter[9] estimating attitude quaternion and the bias of angular velocity measured by IRU. The satellite estimates its attitude every 100 msec. The output noise of IRU is so small that the random error of the estimated attitude of the satellite is also small. Timing synchronization of STT exposure and attitude determination is also important when the target attitude is changing such as during imaging the ground surface. For achieving this, the main computer of the satellite sends a timing signal to STT and update satellite attitude at signal timing after receiving quaternion from STT. With these designs, CE-SAT-IIB determines its attitude with 10 arcsec or better accuracy during tracking the center of the earth.

Attitude Control

Quaternion feedback method[10] are mainly used to calculate control torque. Target attitude is calculated on-board according to the target of pointing and the position of the satellite. For example, during ground tracking, the satellite calculates its target attitude according to the coordinate position of the target and the position of the satellite. Points on the ground, the center of the earth, the sun, and inertial targets are selectable as the pointing target, and any direction of the satellite can be directed to the pointing target.

When the difference between the target attitude and the current attitude is large, the satellite calculates the reference attitude trajectory to converge attitude rapidly. This makes it possible to change the attitude quickly and get images of different targets in a short time.

With high accuracy of IRU measurement and attitude determination, high feedback gain can be used. This realizes high stability and rapid attitude control.

VARIOUS IMAGING WITH PRECISE, AND RAPID ATTITUDE CONTROL

With the ADCS described above, various imaging is available for CE-SAT-IIB.

Imaging with one-point tracking

During this imaging, the satellite continuously tracks the target point on the ground. Figure 6 shows attitude control of the satellite during one point tracking.

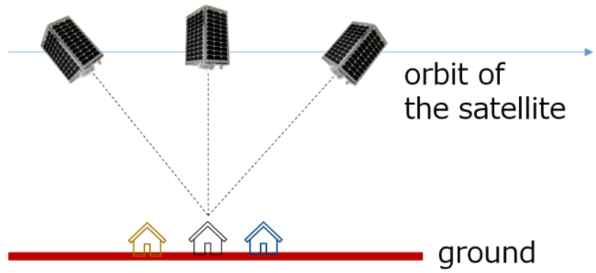

Figure 6: One-point tracking

This makes it possible to take images with long exposure time. Thus, images of moonlit ground can be taken without any artificial light. Additionally, it is also possible to take movies of the target point and get more information than single image. For example, moving objects like cars on highways and ships entering a port can be observed directly.

Tiling imaging

It is also possible to change the target point during ground tracking. As a result, tiling imaging is available. To maximize imaging area and get clear images without "camera shake", the satellite start getting an image right after target pointing control convergence, and after exposure, the satellite start changing the target point again. Figure 7 shows the attitude control of the satellite during tiling imaging.

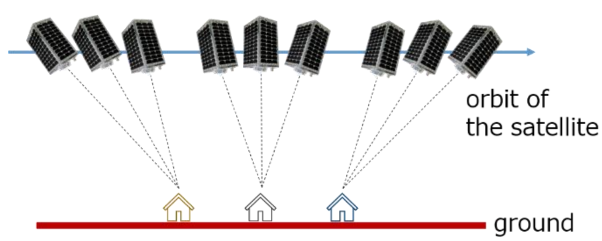

Figure 7: Tiling imaging

With this imaging, the satellite can get images of large area even when imaging night ground surface. For example, square tiling imaging is possible with changing target repeatedly (Figure 8).

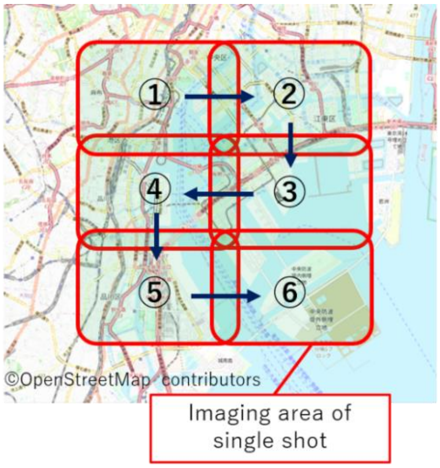

Figure 8: Square tiling imaging

Extended push-broom

In daylight imaging, push-broom imaging is also possible. CE-SAT-IIB is capable of both along-track push broom and cross-track imaging. During along-track imaging, the satellite tracks the center of the earth and continuously gets images. Figure 9 shows the attitude control of the satellite during along-track push-broom imaging.

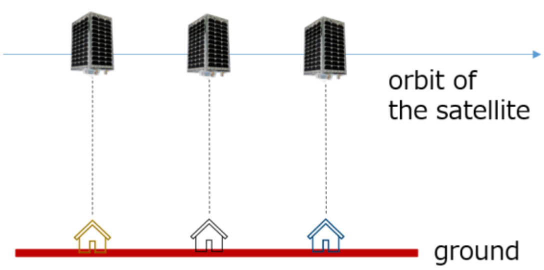

Figure 9: Push-broom imaging

It is also possible to change temporal resolution of imaging by selecting imaging interval and overlap rate of imaging area. This is why we call this imaging "extended" push-broom. Figure 10 shows a sample image of extended push broom.

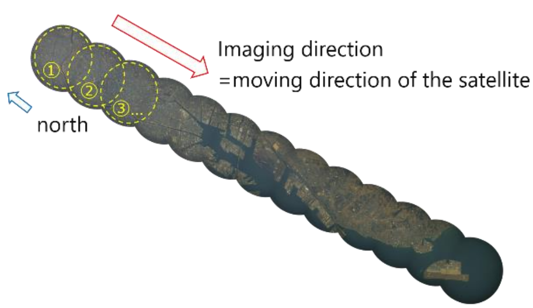

Figure 10: Extended push-broom (along-track)

Cross-track push-broom and multi-line push-broom are also available. CE-SAT-IIB can take 300 km or longer length of image in a shooting pass in cross-track push-broom. In multi-line push-broom, the imaging target moves during imaging. Figure 11 shows a sample image of multi-line push-broom.

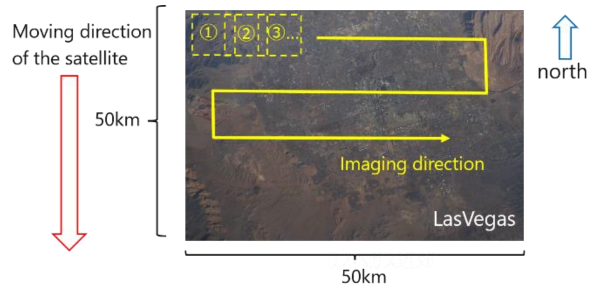

Figure 11: Multi-line push-broom

Only 1ms or shorter exposure time is needed in daylight imaging, and the satellite can move the imaging area during exposure without "camera shake". This is the difference between multi-line push-broom and tiling imaging.

Imaging with inertial pointing

CE-SAT-IIB can also get images of stars with inertial pointing. With the high pointing stability of the satellite, 10 seconds or longer exposure time is possible and nebulas can be photographed. Figure 12 shows the attitude control of the satellite during inertial tracking.

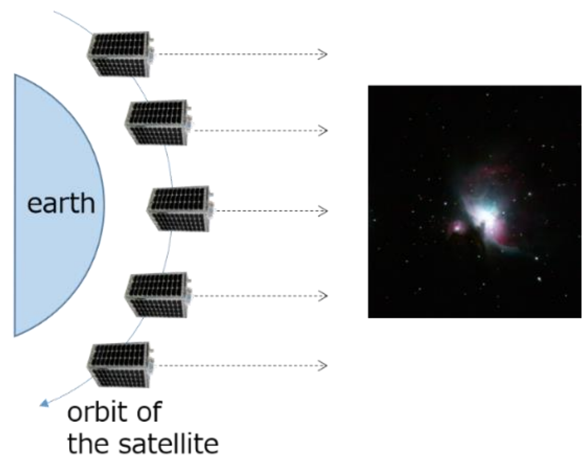

Figure 12: Imaging with inertial pointing

Additionally, high-speed moving objects including satellites and space debris can be photographed with short exposure time utilizing the high sensitivity of the UHSC.

ON-ORBIT SOFTWARE UPDATE

In addition to hardware development, CEI has been updating software of the satellite and components on orbit to improve ADCS and add new functions. Table 6 shows the history of on-orbit software updating of CE-SAT-IIB.

Table 6: On-orbit software updating of CE-SAT-IIB

Date	Target	Contents of Updating
21/1/25	STT	Improvement of star detection algorithm
21/3/16	Main Computer	Improvement of attitude control
21/4/6	STT	Improvement of sun exclusion angle
21/6/4	Main Computer	Improvement of attitude determination
21/6/10	STT	Improvement of star detection algorithm
21/10/19	STT	Reduce power consumption
22/1/13	Main Computer	Improvement of attitude determination
22/7/14	Main Computer	Adding new function: real time image download
22/9/12	Main Computer	Improvement of attitude control
22/12/20	Power Controller	Improvement of heater control
22/12/22	Main Computer	Improvement of orbit determination
23/3/2	Main Computer	Improvement of attitude determination

We developed a secure method of on-orbit updating. With this method, we can update software such frequently.

OPERATIONAL RESULTS

Imaging of night & moonlit ground

1. One-point tracking

On April 7, 2023, CE-SAT-IIB took continuous images of the Salt Lake airport. The satellite took 40 images with 4 fps and 200 ms exposure. Figure 1 is one of continuous images. Figure 13 shows the angular velocity of the satellite during one-point tracking. The start timing of precise attitude control for imaging is shown as 0 s. The satellite tracked the center of the earth until 300 s and estimate the output bias of the IRU. After that, the satellite started the maneuver in order to switch geo-central tracking to ground tracking.

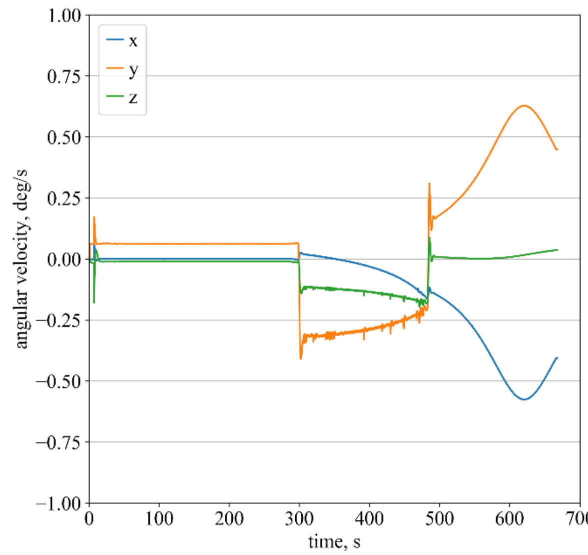

Figure 13: Attitude angular velocity of CE-SAT-IIB during one point tracking sequence

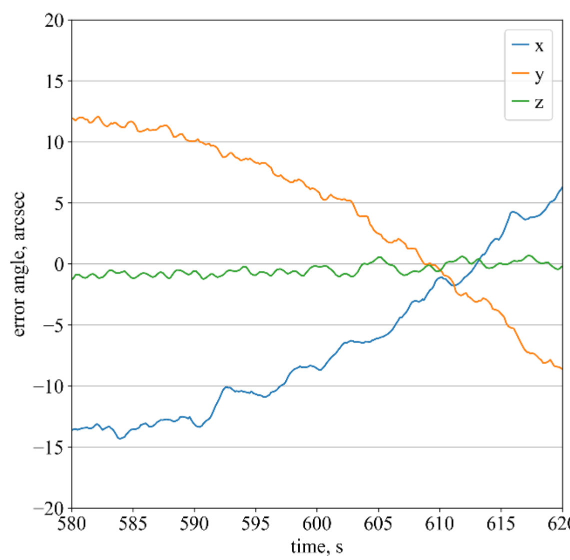

Figure 14: Euler angle error deviation of attitude control during imaging with one point tracking

Continuous imaging started at 595 s and ended at 605 s. Figure 14 shows the Euler angle of error deviation during imaging. The satellite got images with keeping error deviation lower than 10 arcsec in each axis. With this pointing stability, we can find moving objects like cars on highways, and aircrafts on taxiways in these images. (Figure 15)

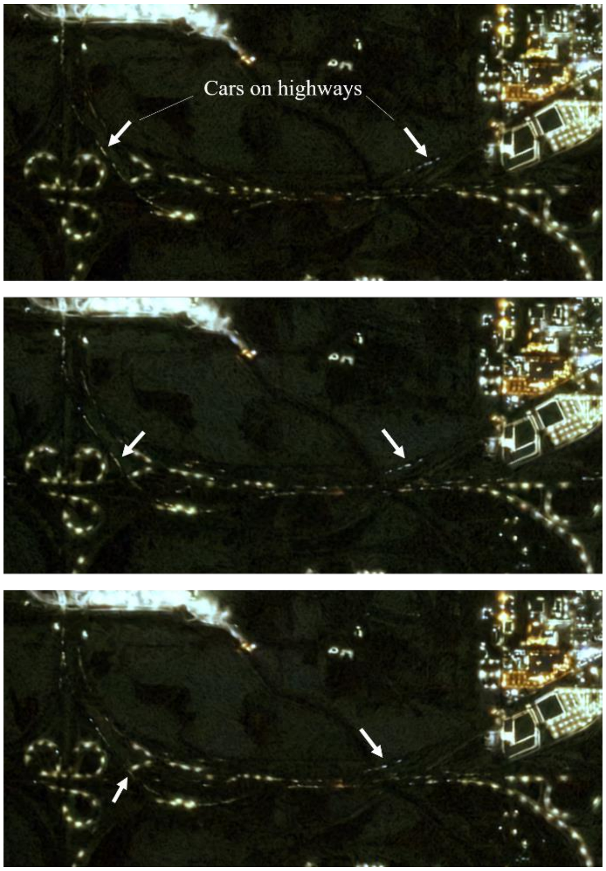

Figure 15: Cropped continuous images of Salt Lake City (5 sec interval)

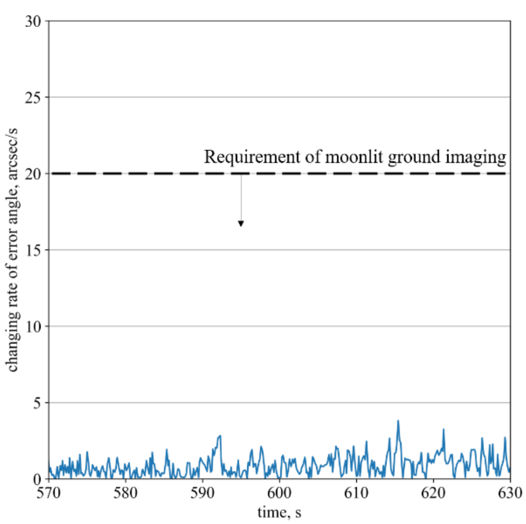

Figure 16: changing rate of error deviation angle during imaging with one point tracking

Figure 16 shows the changing rate of error deviation angle during imaging. Changing rate is lower than 3 arcsec/s during imaging and this is quite lower than the requirement of moonlit imaging. Due to this stability of tracking, up to 1800 ms exposure time is now available.

Figure 17 shows an image of moonlit desert taken with this longer exposure.

Figure 17: Moonlit image of desert taken with 1800 ms exposure time (Dune 45 viewpoint in the Namib Desert)

Here we can see sandy ridges and dried up rivers as if it is a daylight image. This shows the satellite can get images of moonlit ground without any artificial light.

2. Tiling imaging

On April 13, 2023 CE-SAT-IIB got a tiling image of Phoenix city. The satellite taken 9 images with 120 ms exposure.

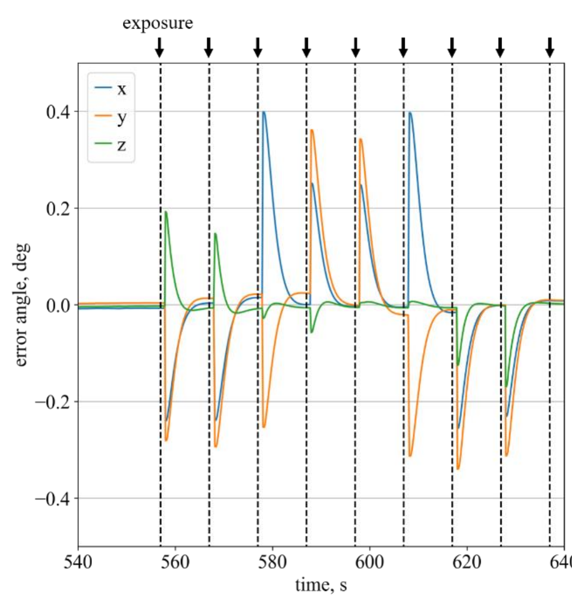

Figure 18: Euler angle error deviation of attitude control during tiling imaging

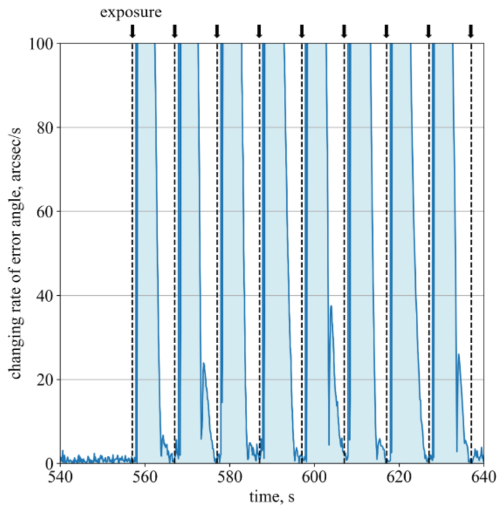

Figure 19: Changing rate of error deviation angle during tiling imaging

Figure 18 shows the angle error deviation of attitude control. Images were taken with 10 sec intervals and the first imaging started at 557 s in the figures. Here we can see the satellite achieved tiling imaging with changing target point and starting exposure after control convergence. Figure 18 also shows the satellite took images with little but not zero error attitude angle, but pointing stability is much more important for achieving night tiling imaging. Figure 19 shows that the satellite started getting each image with keeping the error angle changing rate under 10 arcsec/s. This rate is enough to get clear images. Figure 20 shows a tiling image of Phoenix City in the USA. The imaging area of this figure is about 15 km square. As we can see, the satellite can get a large area of images even in the night.

Figure 20: Tiling images of Phoenix city

Push-broom Imaging

1. Along-track push-broom

On March 6, 2023, CE-SAT-IIB took images of Nagoya city in Japan with along-track push-broom.

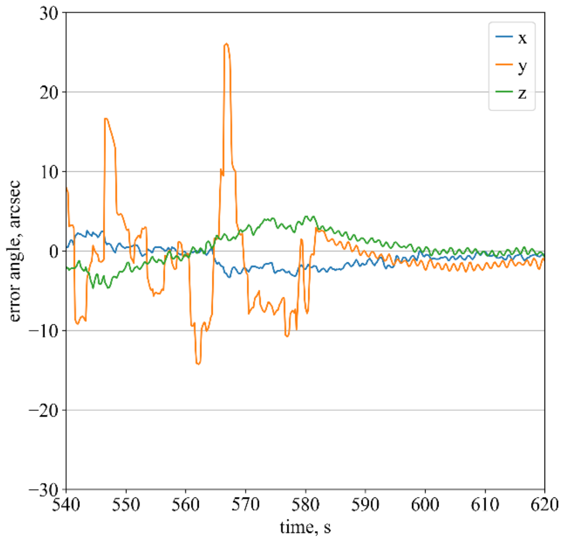

Figure 21: Euler angle error deviation of attitude control during along-track push-broom

Figure 21 shows Euler angle error deviation during push-broom imaging. Push-broom imaging started at 595 s and ended at 605 s. Bias estimation of IRU ended at 580 s in order to get images with higher pointing stability. As we can see, error deviation angle is lower than 3 arcsec during imaging. Because the satellite has only one STT and bore-axis of it is directed to y-axis of the satellite, error angle of y-axis is larger than other axes. Nevertheless, root mean square of error angle is lower than 8 arcsec even during bias estimation. Figure 22 shows push-broom image of Nagoya city. The satellite has ability to get up to 1000 km length of images, and this image is cropped version. Attitude control is so stable that images can be merged into a single image covering large area of the ground.

Figure 22: Push-broom image of Nagoya city

2. Multi-line push-broom

On November 30, 2022, CE-SAT-IIB got images of Las Vegas with Multi-line push-broom. Figure 23 is a combined image of 50 images. Imaging area is about 50 km square. This imaging was achieved by continuously changing the target of ground tracking. With the UHSC, only 0.16 ms of exposure time is needed for daylight imaging. This makes it possible to move the imaging area during exposure and get images of large areas.

Figure 23: Multi-line push-broom image of Las Vegas

Imaging with Inertial Pointing

On October 26, 2022 CE-SAT-IIB took images of Orion Nebula. Figure 24 shows angle error deviation during imaging.

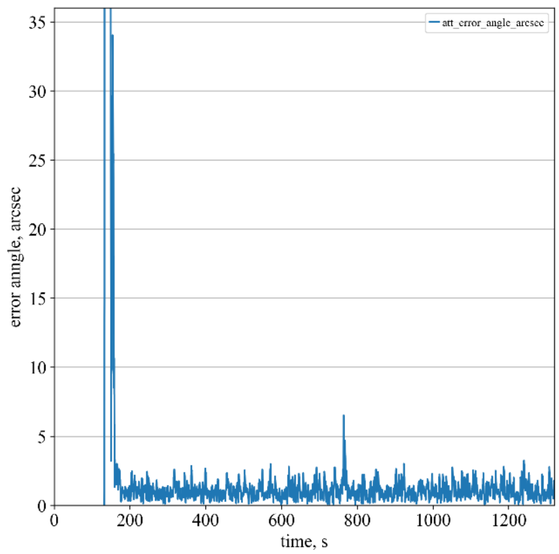

Figure 24: angle error deviation of attitude control during imaging Orion Nebula

Imaging started at 800 s and ended at 1200 s in the figure. The satellite took images with keeping the error deviation of attitude control lower than 2 arcsec (RMS). As a result, the satellite got clear images with 10s or longer exposure time. Figure 25 shows a sample image of Orion Nebula.

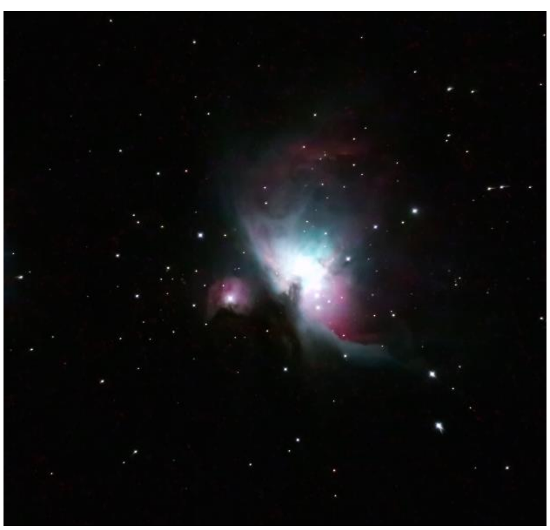

Figure 25: Sample image of Orion Nebula taken by CE-SAT-IIB sub-camera

The combination of the UHSC and precise ADCS is also applicable to Space Situational Awareness. As we see in Figure 22, the UHSC can image daylit objects with 0.16 ms or shorter exposure time. The satellite also can get images with inertial pointing. This means, the satellite has ability to image on-orbit object in daylight. Figure 26 shows an image of ISS taken by UHSC.

Figure 26: ISS image taken by UHSC

This image was taken 235 km away from ISS. With the shorter photographing distance, the better image resolution can be achieved. CEI is now updating both cameras and ADCS in order to get high resolution images of on-orbit objects.

FUTURE PLAN

Next projects for higher resolution, higher sensitivity, and larger area observation

CEI is now developing new generation satellites. With hardware improvement and software updates, these satellites will get a larger area of images with higher sensitivity and higher resolution. Additionally, wider band observation is also planned.

Constellation

CEI also has technology and expertise in mass production and we are considering building satellites for constellations.

CONCLUTION

CEI developed ADCS and camera systems including UHSC for moonlit imaging and demonstrated them by launching and operating CE-SAT-IIB. CEI is continuously updating the software of the satellite on orbit for improving its pointing stability and adding new functions. Now the satellite has the ability to take moonlit ground with 1800 ms or longer exposure time and this makes it possible to get color images of night deserts like imaging in daylight.

Additionally, various imaging is possible with the ADCS. Not only one-point tracking, tiling imaging, and even multi-track push-broom are also available. This means we can change the area, sensitivity, and temporal resolution of imaging by selecting the target of tracking, exposure time, and imaging interval. Moreover, the satellite can take images of satellites and space debris on-orbit with inertial pointing. This various imaging will widen the usage of satellite imaging. CEI continues to achieve higher resolution, higher sensitivity, and larger area observation.

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