SSC19-XII-04

Development and Initial On-orbit Performance of Multi-Functional Attitude Sensor using Image Recognition

Yohei Iwasaki, Yuhei Kikuya, Kenichi Sasaki, Toshiki Ozawa, Yusuke Shintani, Yuto Masuda, Kei Watanabe, Hideo Mamiya, Hiroki Ando, Tsuyoshi Nakashima, Yoichi Yatsu and Saburo Matunaga
Tokyo Instutute of Technology
2-12-1-I1-63 O-okayama, Meguro-ku, Tokyo, 152-8552, Japan; +81-90-4916-0628
iwasaki@lss.mes.titech.ac.jp

ABSTRACT

This paper describes a multi-functional attitude sensor mounted on the “Innovative Satellite 1st” led by Japan Aerospace Exploration Agency which was launched in January 2019. In order to achieve the high accuracy determination in low cost, we developed a novel attitude sensor utilizing real-time image recognition technology, named “Deep Learning Attitude Sensor (DLAS)”. DLAS has two type of attitude sensors: Star Tracker(STT) and Earth Camera (ECAM). For the low-cost development, we adopted commercial off-the-shelf cameras. DLAS uses real-time image recognition technology and a new attitude determination algorithm. In this paper, we present the missions, methods and system configuration of DLAS and initial results of on-orbit experiment that was conducted after the middle of February 2019, and it is confirmed that attitude determinations using ECAM and STT are performed correctly.

INTRODUCTION

A high performance and low cost attitude sensor called “Deep Learning Attitude Sensor (DLAS)” was developed[1),2)] and mounted on a Japan Aerospace Exploration Agency (JAXA) satellite: ”RAPid Innovative payload demonstration Satellite 1 (RAPIS-1).” RAPIS-1 was launched by JAXA’s EPSILON 4 rocket on January 2019 and is currently under operation. In the development of DLAS, commercial off-the-shelf (COTS) products were screened through radiation tests enable lower development cost. Image recognition technology was adopted in DLAS to achieve higher performance for attitude sensors. This technology can also reduce the amount of downlink data because the satellite with DLAS autonomously recognizes and screens useful data.

This paper describes the missions of DLAS, the system configuration, and introduces attitude determination methods. Also, as a report on the results of on-orbit experiments, we introduce adjustment of Earth Camera (ECAM) and Star Tracker(STT) parameters on orbit and the initial results of the image recognition and the attitude determination.

MISSIONS

DLAS has mainly three missions[1),2),3)].

1) Demonstrate low cost and high performance attitude sensors

DLAS introduced COTS products to develop the STT and ECAM whereas spacecraft generally employs aerospace-proven devices that are guaranteed to have high radiation tolerance and high reliability. We designed DLAS from both hardware and software aspects to ensure high reliability even with COTS products, and as a result, we can obtain an elementary technology for advanced design and manufacture.

2) Demonstrate real-time on-orbit image recognition

ECAM execute real-time image recognition to a picture captured by a visible light camera in ECAM. In this project particular, ECAM recognizes the geographical features such as ocean, land (forest, desert, city etc.) and clouds, whose result is applied to attitude determination. The real-time image recognition technology can also be applied to advanced applications such as disaster monitoring, security surveillance and astronomical observation.

We also developed high performance image recognition algorithm[1),2)] and demonstrate in orbit, since it is necessary to process the image recognition with limited computational resources.

3) Demonstrate a new type of attitude determination method using ECAM

DLAS demonstrates an attitude determination with small, wide range, visible light camera. This mission enables earth observation camera to attitude determination and

can achieve high accuracy and reliability estimation associating with STT and MEMS gyro sensors.

DLAS first detects the earth edge in the captured image and determine 2-axis attitude (the nadir direction), then, determine 3-axis attitude determination by land pattern matching or angle velocity estimation with camera motion estimation.

The usage of imaging devices can realize bus miniaturization and cost down by dual use of earth camera for observation and attitude determination even for resource-poor small satellites.

The success criteria of the missions are shown in Table 1.

Table 1: Success Criteria

Level	Criteria
Min	Function checkout in orbit - Evaluation of the image quality - H/W checkout - Downlink the images and HK data
Full	Demonstration experiments - On-orbit attitude determination - Evaluation of the accuracy - Accumulation of the training data (500 frames) - Performance target: - ECAM: land/cloud/ocean (70 %) - STT: detection of 5 mag stars(70 %) - Training data: 500 frames
Extra	Long term demonstration and Revision - Accumulation of the training data (1000 frames) - Monitoring degradation of the devices Performance target: - ECAM: Attitude accuracy ≤ 5 deg - STT: Attitude accuracy ≤ 600arcsec - Mission life: ≥ 1 year

SYSTEM CONFIGURATION

As shown in Figure 1, DLAS consists of three components: two camera units (X and Y) and a controller unit. The camera unit has 2 types of image devices: wide field of view (FoV) camera for a high luminance object and narrow FoV camera for a low luminance object. Each Camera unit has two ECAMs on a baffle of the STT as shown in Figures 2. Since these camera units can be operated independently, the DLAS can continue to work for the missions even if one of them would be failed.

The controller unit has two Single Board Computers as Mission OBCs, an electric power system (EPS) and a micro controller for command and data handling (CDH). Figure 2 shows an overall outlook of the controller unit. We employed a single board computer for each Mission OBC which runs for image processing and attitude determination.

In CDH a microcontroller was adopted that has low performance but has high radiation tolerance and utilized for interface with the satellite bus and EPS for monitoring and management of temperature and OBC. When the CDH detects that the Mission OBC has errors or is frozen, it commands the EPS to shut down or reboot the Mission OBCs.

As for the interface with the satellite bus, DLAS has 2 communication lines. One is a low speed line for sending command or HK data which is all communicated via CDH. The other is a fast speed line for large data handling such as captured image, and it does not communicate via CDH and is unidirectional to the satellite bus.

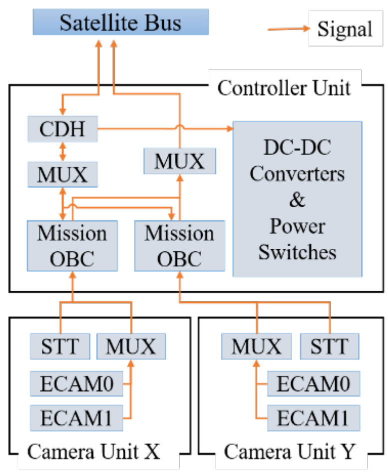


Figure 1: System Diagram

Figure 2: DLAS Controller Unit and Camera Unit

METHODS OF ATTITUDE DETERMINATION

This chapter presents the methods of attitude determination of ECAM and STT[1),2),4)].

ECAM

The 3-attitude parameters in ECAM are defined as shown in Figure 3. An azimuth angle θ and an elevation angle φ describe the nadir direction in the sensor fixed coordinate system. And the third attitude parameter ψ is defined to describe the angle around the nadir vector.

The method of 3-attitude determination using picture of ECAM consists of two steps: 1) determination of the nadir vector direction called 2-axis attitude determination and 2) determination of an attitude around the nadir vector called 3-axis attitude determination.

As for the first step, DLAS determines the nadir vector from the earth edge on the picture taken from ECAM. Unlike horizon sensors, only a part of the earth may be pictured since the altitude of spacecraft is supposed to be low and the ECAMs are not omnidirectional while ECAMs have wide FoV. Therefore, DLAS has to determine the nadir vector from a part of the earth on a picture.

The earth's edge is pictured like an arc of a circle, but the edge is distorted if a center of the arc is not on the center of the picture. It is difficult to determine the precise center of the circle which is the nadir direction directly. Thus, the edge is projected to an imaginary unit sphere as shown in Figure 4. Since the projected circle on the unit sphere is not distorted, if elliptic shape of the earth is ignored, it is easy to determine the center C of the circle. Note that the direction to the center C from the origin O is the nadir direction and the azimuth angle θ and the elevation angle φ as shown in Figure 3 can be determined.

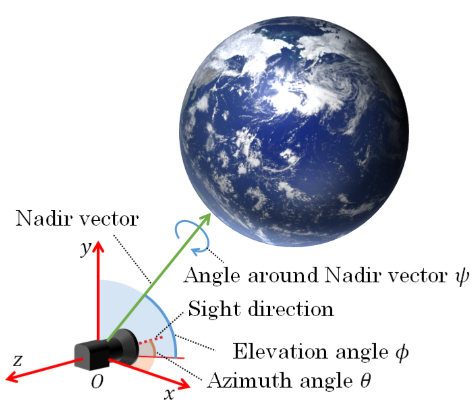


Figure 3: Definition of Attitude Parameter

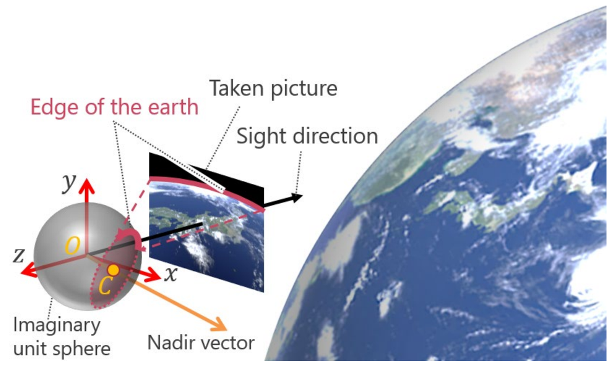


Figure 4: Nadir Vector Determination

Next to the 2-axis attitude determination, the attitude angle around the nadir vector ψ is determined using surface patterns of the earth. The main idea is to compare the surface patterns on the picture with map data preloaded on DLAS. The simplest way is to compare the picture with the whole maps directly but it is not computationally feasible. In addition, the matching is also difficult because taking pictures is dependent on sunlight or weather condition and so on. Thus, as a preprocessing, DLAS identifies and categorizes the surface of the earth with image recognition algorism utilizing a neural network model.

Before launch, we used images sent from the ISS as training data as shown in Figure 5 and two type of color spaces, HSV and RGB for the training of the neural network[1),2)].

DLAS performs the earth surface categorization in the following two procedures as shown in Figure 6. 1) Divide the picture to every 16×16pixels square block named "window". Since the ECAM picture is 3280×2464 pixels resolution, the picture is divided into 31570 windows. 2) Categorize each of the windows into ten classes using neural networks: thick cloud, thin cloud, foggy cloud, sea, forest, yellow desert, red desert, space, black land and city. This enables to match without disturbance such as cloud.

Figure 5: Earth Image Taken from the ISS [7)]

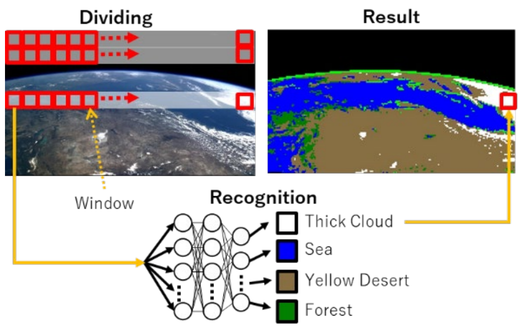


Figure 6: Image Recognition Sequence

In the next step, DLAS narrows down the candidate sites on the map with both GPS data and the 2-axis attitude determination result.

Finally, matching the picture with the map is processed to provide the attitude angle ψ around the nadir direction. To deal with the distortion of the image, a coordinate transformation is suggested. We conducted a projection for both the images taken by DLAS and map data as shown in Figure 7, but it requires the generation of images corresponding to each value of ψ and results in a large calculation cost.

In order to reduce the computational cost and improve the matching speed, we propose a modified matching method on a new plane called a FoV (Field of View) screen, as shown in Figure 8[4]. The FoV screen is located between the Earth and the satellite at a distance of unit length from the satellite, and is perpendicular to the nadir vector. As shown in the upper part of Figure 9, the matching is performed while rotating the projected image along this circle to determine the attitude ψ around the nadir vector. Furthermore, as shown in Figure 9, converting to polar coordinates can reduce the amount of calculation when updating ψ.

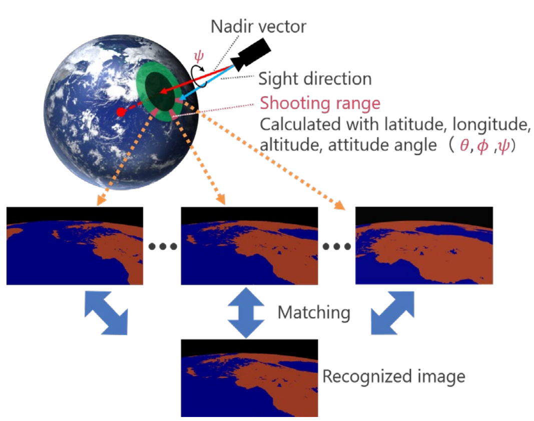


Figure 7: Matching Process on Image

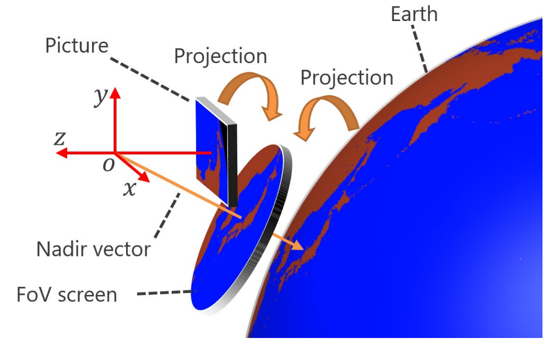


Figure 8: Projection of Image and Map Data onto FoV Screen

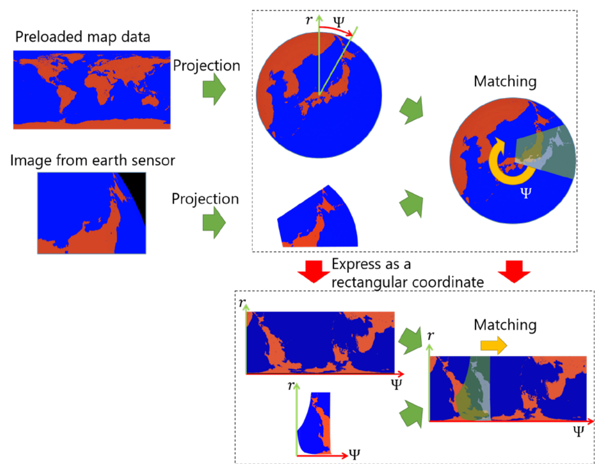


Figure 9: Matching between Image from Earth Sensor and Preloaded Map Data

STT

The process of attitude determination using STT consists of three steps: 1) "extraction of point source" shown in Figure 10 that picks up bright spots from the image, 2) "identification of stars" that identifies the star by comparing the geometric pattern of bright spots and star catalogs, 3) "calculation of attitude" that calculates the attitude angle using stars' coordinates in inertial frame and body frame.

Extraction of point source affects the attitude determination accuracy, so it is important to extract stars correctly in this step. When calculating the position of the point source in the image, the center of point source is calculated using peak search. At this time, cosmic rays are reflected in the image as bright spots, and they are misrecognized as stars. At this time, cosmic rays are reflected in the image as bright spots, and they are misrecognized as stars. This time, we use a kernel to distinguish between cosmic ray point sources and star point sources.

When matching with star catalogs, the matching is performed using geometric patterns. The Pyramid algorithm is used as a geometrical pattern. The Pyramid algorithm is a method that uses the positional relationship of a total of four point sources of three stars close to one star as a geometrical pattern [4)]. This time, as shown in Figure 10, in order to strengthen the robustness, a total of five point sources using four nearby stars are used.

Finally, the pointing direction and roll angle of STT are calculated using QUEST method [5)].

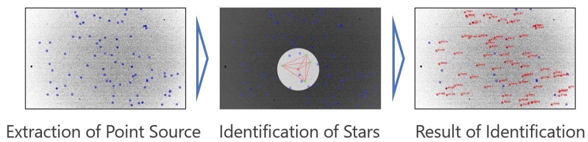


Figure 10: Extraction of Point Source and Identification of Stars

ON-ORBIT PERFORMANCE

On-Orbit Operation Plan

As it shows in Table 2, operation is mainly divided into 4 sections. Initial operation confirms all components checkout. In calibration operation, image and attitude determination result for ECAM and STT is obtained to calibrate the parameters with data analyses on ground for capturing the image and attitude determination. Calibration operation is assumed to take around 1 month.

Nominal operation started regular image capturing and attitude determination experiments in the aim of full success. This phase is assumed to take around 11 months and even during this phase, parameter uplink can be conducted as needed.

As for long term operation, until the very end of satellite operation, DLAS maintains to obtain images and attitude determination experiments in the aim of extra success. Furthermore, some additional experiments with severer cases are also conducted for more practical sensor development, such as attitude determination experiment during attitude maneuvering and obtain data from it.

Currently, Calibration operation phase has been completed and Nominal operation phase is in progress.

Table 2 : DLAS ON-Orbit Operation

Phase	Contents	Term
Initial Operation	- DLAS components checkout	1 day
Calibration Operation	- capturing images and Attitude determination: 30 frames/ day - parameter calibration	1 month
Nominal Operation	- accumulation of images and attitude determination (Extra Success) - additional experiment - parameter calibration	11 month
Long Term Operation	- accumulation of images and attitude determination (Extra Success) - additional experiment - parameter calibration	12 month

ECAM

ECAM captured the earth with auto parameters as a default setting, but the earth image was saturated because of the intensity gap between the earth and deep space. Therefore, we adjusted shutter speed (SS) and auto white balance (AWB) in ECAM. The result of adjusting the SS is shown in Figure 11. Based on this result, we searched for the best value of exposure value (EV) between 14 and 16 as shown in Figure 12. In response to this result, we set SS to 1/4000 and AWB to sun. As a result, Figure 13 clearly shows the earth's ocean and clouds instead of showing the halation.

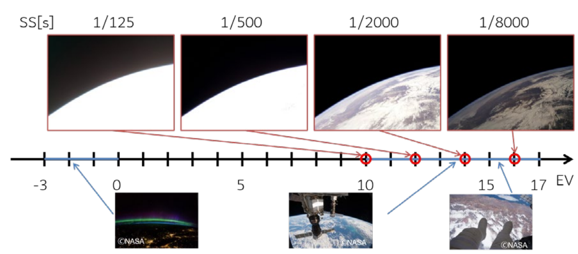


Figure 11 : Result of Adjusting the Shutter Speed

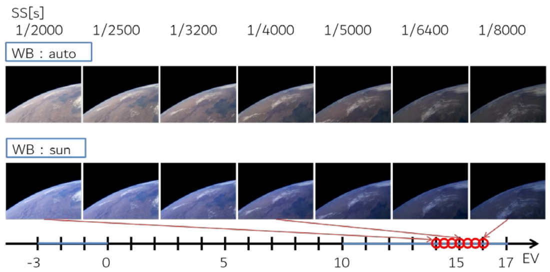


Figure 12 : Result of Adjusting the Shutter Speed and White Balance

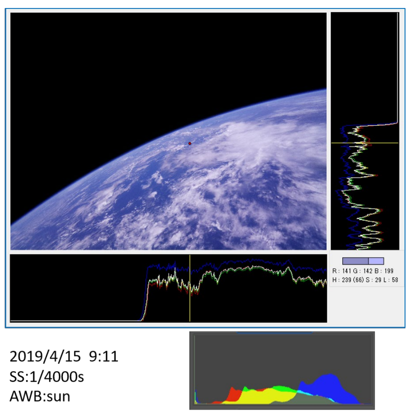


Figure 13 : Earth Image after Adjusting Parameter

Figure 15 shows classification of the image taken by DLAS on the ground using the pre-learned classifier. The results are shown in Figure 15 where a class description in Figure 16 is used. Classification accuracy is poor due to differences in color balance between DLAS image and ISS one.

We conducted relearning using the image taken with DLAS. Learning conditions are shown in Table 3, and dataset are shown in Table 4. Classification results using relearned classifier are shown in Figures 17. Figure 17 shows that the image segmentation works better with RGB color space than the that with HSV. In a learning with RGB color space, relearned model is successfully conducted the image segmentation based on the geographical features. Even thick and thin cloud classification is appropriately implemented, which indicates that the color distribution besides the color intensity in the window is correctly learned with the mode. This also implies that image classification with this model can be successfully achieved when it shares the common camera imagery parameter. The dataset is, however, still not enough to crop the window of the all classes and validate the model. In addition, the "Ground Truth" model also needs to be constructed for more accurate algorithm validation.

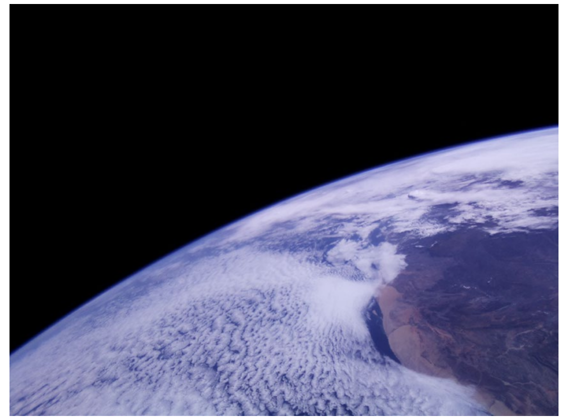
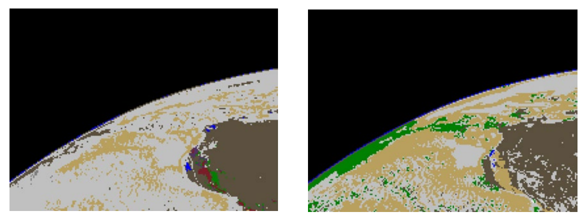


Figure 14 : Earth Image (Angola) Taken by DLAS



(a) Color Space : RGB (b) Color Space : HSV

Figure 15: 10 Classes' Scene Classification Using Pre-learned Classifier

Thick Cloud	Thin Cloud
Sea	Foggy Cloud
Black Land	Red Land
Forest	Yellow Land
City	Space

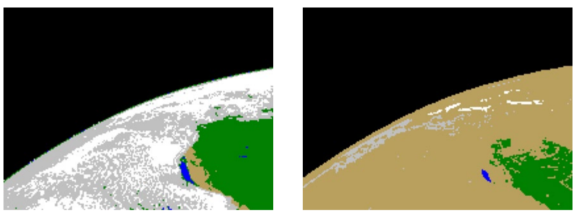
Figure 16: Class Description

Table 3 : Relearning Conditions

Model	Color Space	Number of Class
MLP (1 Hidden Layer)	RGB, HSV	6

Table 4 : Dataset Description

Number of Training Data	Number of Testing Data	Classes
4000	1000	Thick Cloud
4000	1000	Thin Cloud
8000	2000	Sea
4000	1000	Forest
8000	2000	Desert
8000	2000	Space



(a) Color Space : RGB (b) Color Space : HSV

Figure 17: 6 Classes' Scene Classification Using Relearned Classifier

We also executed attitude determination on the ground. In Figure 18, red dots represent the detected earth edge and yellow curve is estimated earth edge calculated using attitude angle (θ , ϕ) and altitude. Since the yellow curve fit the actual earth edge, nadir vector could be estimated correctly.

Using the result of nadir vector determination and GPS data, map data and classification result were projected on FoV screen as in Figures 19 and 20. In this case, many land areas are covered with clouds, but areas identified as clouds are excluded in the matching process. As shown in Figure 21, comparison can be made only on the visible land and sea, and the attitude of the third axis ψ can be accurately estimated. The above processing is performed using on-board algorithm, and can execute attitude determination on orbit by optimizing the classifier.

By comparing the above results with the attitude of the satellite bus, it is possible to measure the alignment error, and after performing the alignment calibration, we evaluate the detailed attitude determination accuracy.

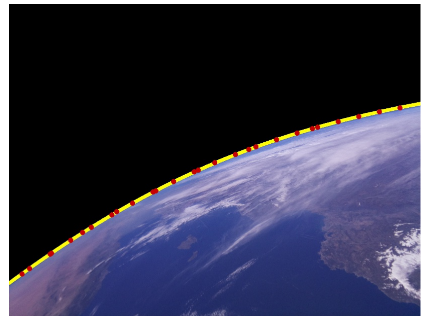


Figure 18: Result of Nadir Vector Determination

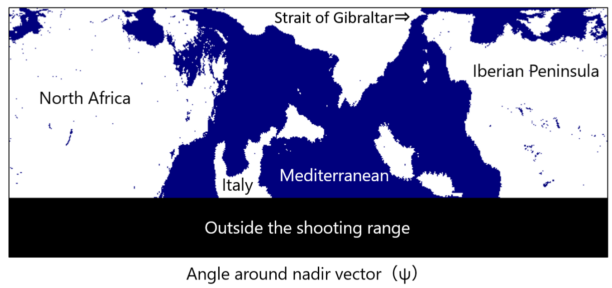


Figure 19: Map Data Projected on FoV Screen

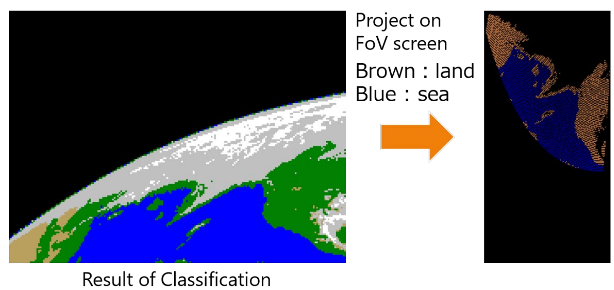


Figure 20: Classification Result Projected on FoV Screen

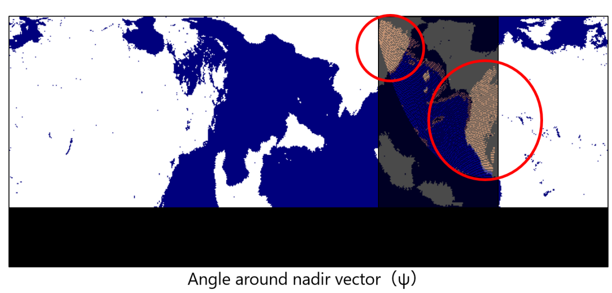


Figure 21: Matching of Classification Result and Map Data

STT

Based on the image taken on the orbit, calibration of the sensitivity of the image sensor and imaging parameters were performed on the ground. It was confirmed that the sensitivity of the image sensor on orbit was almost the same as that on the ground. Figure 22 shows the sensitivity of the sensor on the ground and in orbit. The horizontal axis represents the magnitude of the photographed star, and the vertical axis represents signal strength from the star image obtained by shooting. The purple, green and blue lines represent the sensitivity when photographed on the ground, and the red line represents the sensitivity calculated from the data obtained on the orbit. There is almost no change in sensitivity on the orbit. As shown in Figure 23, detection limit decreases by 1.5 grade by setting exposure time to 1/10. If readout noise and dark current do not work, the signal intensity should be 1/10 at 1/10 of the exposure time, so detection limit should decrease by 2.5 grade in simple calculation. In this case, it is expected that the read noise is slightly improved by increasing the gain, and that one grade is obtained for that. Dark current is about 1 count per pixel in any case, and hardly contributes to SN.

Also, as a result of investigating the damage condition of the image sensor by the cosmic ray, it can be seen that the number of damaged pixels is increasing at a pace of 5 pixels / day.

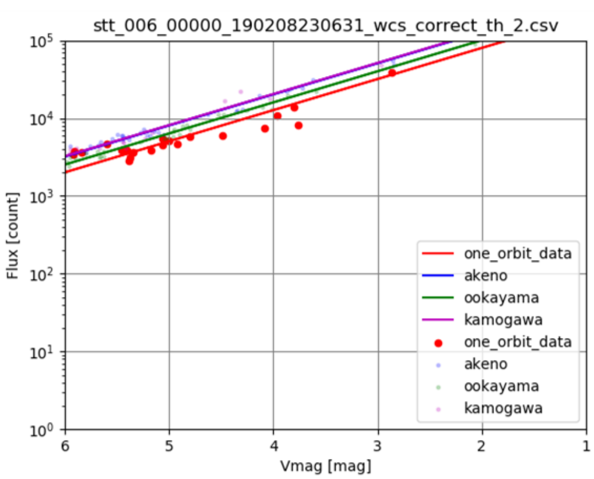
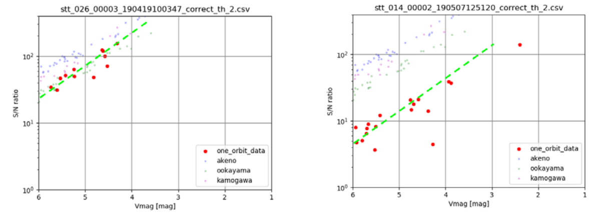


Figure 22 : Sensitivity of Image Sensor, Exp = 100ms, Gain = 0dB



(a) Exp = 100ms, Gain = 0dB

(b) Exp = 11.21ms, Gain = 12dB

Figure 23: Detection Limit of Image Sensor

CONCLUSION

This paper described the mission, the system configuration, and the attitude determination methods in DLAS consisting of ECAM and STT. DLAS was launched into orbit in January 2019, and the initial on-orbit results of DLAS was also introduced. First, adjustment of the camera parameters was conducted: We re-conducted the ground simulation using images taken by ECAM on-orbit since image identification by pre-learned classifier before launch did not work well. In addition, we confirmed the performance of attitude determination to show the feasibility of the proposed method. Regarding to STT, we also performed parameter adjustment and sensitivity analysis of STT.

ACKNOWLEDGMENTS

This work is supported by The Mitsubishi foundation Research Grants in the Natural Sciences and The Precise Measurement Technology Promotion Foundation, JSPS KAKENHI Grant Number 941864, and JSPS KAKENHI Grant Number 17H01349.

REFERENCE

1. Koizumi, S., Kikuya, Y., Sasaki, K., Masuda, Y., Iwasaki, Y., Watanabe, K., Yatsu, Y., and Matsunaga, S., “Development of Attitude Sensor using Deep Learning”, Proceedings of Conference on Small Satellites, Utah, U.S.A, August, 2018.
2. Kikuya, Y., Sasaki, K., Koizumi, S., Masuda, Y., Ozawa, T., Shintani, Y., Yatsu, Y., and Matunaga, S. “Development of Low-cost and High Peformance Attitude Sensor applying Newral-network Image Recognitng Technology”, Proceedings of i-SAIRAS, Madrid, Spain, June, 2018.
3. Watanabe, K., Kikuya, Y., Sasaki, K., Ozawa, T., Shintani, Y. Masuda, Y., Iwasaki, Y., Mamiya, H., Yatsu, Y., Matunaga, S., “Development and Ground Evalution of Novel Attitude Sensor with Earth Camera and Star Tracker using Image Recognition”, Proceedings of 32st International Symposium on Space Technology and Science, Fukui, Japan, June, 2019.

4. Kikuya, Y., Iwasaki, Y., Yatsu, Y. and Matunaga, S., “Attitude Determination Algorithm Using Earth Sensor Images and Image Recognition”, Transactions of the Japan Society for Aeronautical and Space Sciences, submitted

5. Mortari, D.; Junkins, J., Samaan, M., “Lost-inSpace Pyramid Algorithm for Robust Star Pattern Recognition,” Proceedings of 24th annual AAS Guidance and Control Conference, Breckenridge, CO, 31 January - 4 February 2001.

6. M.D. Shuster and S.D. Oh, “Three-Axis Attitude Determination from Vector Observations” Journal of Guidance, Control & Dynamics, vol. 4 No. 1 January 1981.

7. NASA, “The-Earth-4K-Extended-Edition”, https://archive.org/details/NASA-Ultra-High-Definition/The-Earth-4K-Extended-Edition_MP4.mp4, Accessed: June, 2019.