Initial Phase AOCS Operation of Infrared Astronomy Satellite “AKARI”
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Abstract
Reported in this paper is the initial phase operation of the attitude and orbit control system (AOCS) of Japanese satellite “AKARI.” AKARI is the first Japanese satellite dedicated to the infrared astronomy. AKARI was successfully launched by M-V rocket from Kagoshima Space center on February 22, 2006. Just after the launch, AKARI faced to a serious problem. It was found that something interferes with the fields of view of two (out of two) sun sensors. The two sensors were out of use in the subsequent AOCS operation. The anomaly prevents us from carrying out the pre-planned initial phase operation, and constrains us to reconfigure the AOCS architecture. The experiences in this recovery operation are mainly reported in the paper. In addition, unexpected continuous orbit rising was observed in the operation. The cause of the phenomenon and its investigation process are also reported.

1. Introduction
AKARI (Fig. 1) is the first Japanese satellite dedicated to the infrared astronomy. It was successfully launched by M-V rocket from Kagoshima Space Center on February 22, 2006 (Japan Standard Time, JST). The mission of AKARI is to make an all-sky survey at infrared wavelength, with much better sensitivity, spatial resolution and wider wavelength coverage than its predecessor, IRAS (Infrared Astronomical Satellite, launched in 1983 by the United Kingdom, the United States, and the Netherlands.) The observation data acquired by AKARI is expected to contribute to various science areas, especially to understand the formation and evolution of galaxies, and to inquire into the formation process of stars and planetary systems.
operation, anomalies are found one after another in the instruments loaded on +y side panel. The anomalies found are,
- No input of the sun light on TFSS (Two-dimensional Fine Sun Sensor).
- Power generation of SAP (Solar Array Panel) approximately 150W lower than predicted.
- Temperature difference between two symmetrically located SHNT (Shunt regulators).
- Temperature of some instruments loaded on +y side panel higher than predicted.
- Beam pattern of SANT (S-band Antenna) different from that measured on the ground.

No longer, it was not supposed as failures of each instruments, but supposed as a systematic anomaly affecting many instruments on +y side panel. And the phenomena are called “+y side panel problem” (Fig. 6). Later, the phenomena were analyzed in detail, and it has been concluded that a part of +y side panel is covered with something. However, the object that covers the panel is not specified in spite of elaborate investigation.

As to AOCS (Attitude and Orbit Control System), two (out of two) sun sensors are affected by the problem and they are out of use in the subsequent AOCS operation (Fig. 7). As other many satellites, sun sensors were planned to play important roles in AKARI’s AOCS operation. Firstly, they were to be used for sun acquisition at the very initial phase. Secondly, as mentioned earlier, to prevent the sun light inflow to the telescope, the attitude of AKARI is strongly restricted after the aperture lid was ejected. Sun sensors were to be used to watch the sun direction to keep the sun in appropriate direction even when the satellite falls into the safe mode. The absence of the two sun sensors prevents us from carrying out the pre-planned operation. However, the difficulty had to be overcome to achieve the mission of AKARI.

Reported in this paper is the AOCS operation of AKARI under the circumstance mentioned above. It covers the...
AACS operation from the launch to the end of the initial phase, i.e. the aperture lid ejection. The topics included are, the operation on the day of launch and the orbit rising problem (another problem arose in the initial phase operation).

2. Operation on the Day of Launch

AKARI was launched by M-V rocket from Kagoshima Space center at 6:28 a.m. on February 22, 2006 (JST). Reported in this section is the operation on the day of launch. Fig. 8 shows the visible paths from the ground stations on the day of launch. The main ground station for the operation of AKARI is Uchinoura space center. Add to that, four more stations (Santiago, Perth, Kirna, and Svalbard) were also assigned for the critical operation on the day of launch. The basic role of the four additional stations was to watch the status of AKARI, and no nominal command operations were planned for these stations. The first command operation was planned to be performed at the Uchinoura path, which was planned at about 11 hours from the launch. Therefore, the critical operations in very initial phase were planned to be performed automatically onboard. A feature to be pointed out about the paths schedule is that, there were no visible paths for about 5 hours after the second Santiago path (SNT #2). Therefore, it was planned to complete the SAP deployment and three axes attitude establishment before SNT #2, so that we could release AKARI in stable condition at SNT #2. In particular, the completions of SAP deployment and the sun acquisition were necessary to secure sufficient power supply to survive the succeeding invisible 5 hours.

Fig. 8 Visible Paths from the Ground Stations

Listed on Table 1 are the planned operation items to be performed up to three axes establishment. AKARI was going to be separated from M-V rocket with the spin rate of 7.5 rpm around z axis. At the first apogee passage, a perigee up maneuver of 25m/s was to be performed. The maneuver was set to cope with the case that the perigee altitude of the injection orbit was extremely low. Therefore, as long as the injection by the rocket was performed properly, the maneuver was not necessary. After the maneuver, the spin rate was to be suppressed, and the SAP was to be deployed. Then the three axes attitude was to be established by firstly searching the sun by NSAS and point $+y$ direction to the sun, and secondly searching the earth by CES (Conical scan Earth Sensor) and point $-z$ direction to the earth. Before the launch, these operation items were planned to be completed before SNT #2.

Table 1 Operations up to Three Axes Attitude Establishment

1. Separation
2. Perigee up maneuver
3. Spin down and rate dump
4. SAP deployment
5. Sun acquisition
6. Earth acquisition
7. Attitude maintenance

In actual operation, because of the "$+y$ side panel problem", NSAS didn’t work properly, and the sequence didn’t proceed as it had been planned. Depicted in the followings are what had been occurred in actual operation.

The first opportunity after the launch that we could know the status of NSAS was the deployment of the fairing of the rocket. It was before the separation and the event was visible from the launch site. The moment that the fairing was deployed, the sun light was input to NSAS and the telemetry shows that NSAS output proper predicted signals. The first visible path after the separation, that is the first Perth path (PRT #1), was about 15 minutes after the launch. The data anomaly of NSAS was firstly detected at PRT #1. The anomaly was not the kind of “perfect blind”, but that of “disordered data”. The next visible path was the first Santiago path (SNT #1), about 45 minutes after the launch. Originally, the perigee up maneuver was planned to be performed at the beginning of this path, and it was predicted to take time to establish the communication link at this path. Additionally, the information about the anomaly was limited at this moment. Then, we decided to monitor the status of AKARI, and didn’t uplink any emergency command at this path. As a result of monitoring at SNT #1, two facts became clear. Firstly, the perigee up maneuver was interrupted at 6 seconds, which was originally planned to continue for 300 seconds. It was supposed to be automatically aborted due to NSAS data anomaly. Secondly, the spin rate was suppressed to the appropriate level, but not in nominal manner. The spin rate was originally planned to be measured by detecting the zero-cross of NSAS data, however, it was supposed to be automatically switched to the measurement by GAS (Geomagnetic Aspect Sensor) data. Based on these facts, it was concluded that NSAS was out of use. And, it was expected that SAP deployment would be performed as planned since the spin rate was suppressed sufficiently, however, it was expected that the sun acquisition would not complete by the next visible path, SNT #2, since NSAS was out of use. As mentioned before, the completion of the sun acquisition at SNT #2 was necessary to secure sufficient power supply for the survival.

At AOS (Acquisition Of Signal) of SNT #2, as had been expected, AKARI continued searching the sun by spinning around z axis. The objective of the operation of SNT #2 was to stop the spin so that $+y$ direction pointed at the appropriate direction, that is the direction of the sun. Instead of NSAS, which was out of use, mainly monitored was the output current (equivalent to the power supply) of SAP. The output current changes sinusoidally as AKARI spins around z axis, and when the current was at the peak, a real time command was sent to stop the spin. Of course, it was rather course to measure the angle between $+y$ direction and the sun based on the power supply, however, it was clear that sufficient power supply was secured. And that’s enough in this situation. AKARI was saved.

Though it was not relied on, the data of NSAS was also monitored as a reference. It seemed that the sun is approaching to the $+y$ direction, that is the signal of the sun seemed to approach the center of NSAS view. However, the signal of the sun suddenly disappeared just before the arrival at the target, and NSAS didn’t trigger to stop the spin. Fig. 9 shows the reproduced data of NSAS output at the sun acquisition. The plots indicate the signal of the sun in the view of NSAS. The center of the view, that is the point (1024, 1024), coincides with the $+y$ direction, the horizontal and vertical axes...
express the direction around $z$ and $x$ axes respectively. The data indicate that the left half of the view seems to generate correct data, since the signal of the sun moved from the left to the right as AKARI span around $z$ axis, and additionally, the signal of the sun seems to approach the center of the view, that is $+y$ direction. On the other hand, the right half of the view seems to generate confused data, and the point of the signal seems not to express the correct direction of the sun. And the point is that, the very center of the view, where the direction of the sun should converge, is in “confused data region”. After all, NSAS caught the signal of the sun in the left half of its view, and the attitude was controlled correctly to point $+y$ direction to the sun. However, the signal of the sun was lost just before the arrival at the target, and the search process was restarted. It was what repeated many times, and it was what observed in SNT #2.

As a result of the “manual” sun acquisition procedure, the minimum necessary condition at the end of SNT #2 was satisfied. At LOS (Loss of Signal) of SNT #2, $+y$ direction was approximately pointing the sun, and AKARI was spinning around $y$ axis in the orbit rate. Only the body rate was controlled based on IRU (Inertial Reference Unit). The power supply, the thermal input, and the communication link to the ground were all in stable conditions.

At the next visible path, the first Kirna path (KRN #1), a real time command was sent to start the earth acquisition. It was performed normally, and AKARI established the normal three axes attitude (see Fig. 5). After the monitoring at several paths at Kirna and Svalbard, the main operation on the day of launch was performed at the first and the second Uchinoura path (USC #1 and USC #2). AOCS RAM (Random Access Memory) program was loaded and run, RW (Reaction Wheel) was run up, and the attitude was started to be controlled by RW instead of thrusters.

At the end of the operation on the day of launch, $+y$ direction was approximately pointing the sun and the body rate around $x$ and $z$ axes are controlled to be zero based on IRU. The body rate around $y$ axis is controlled to be the orbit rate based on CES and IRU. The attitude was controlled by RW. The power supply, the thermal input, and the communication link to the ground were all in stable conditions.

3. Orbit Rising Problem

From right after the launch, it was observed that the semi major axis of the orbit of AKARI gradually increased day by day. The rate of increase was approximately 190m per day (Fig. 10).

The phenomenon didn’t influence the operation instantly. However, in the long term, it was expected to cause the orbit to deviate from the sun synchronous condition, and lead to the prolongation of the time of eclipse to unacceptable level. Fig. 11 shows the prediction of the deviation from the sun synchronous condition (which is expressed as the transition of the angle between the right ascension of the sun and the ascending node of the orbit) and the time of eclipse, assuming that the semi major axis of the orbit would increase in the same rate. Additionally, the increase of the semi major axis (in other words, the increase of the orbit energy) is unusual phenomenon, which suggests that AKARI was ejecting something. Therefore, the phenomenon was called “orbit rising problem” and regarded as the problem to be solved by the ejection of the aperture lid.

To investigate the phenomenon, firstly, the acceleration acted on AKARI was estimated by way of the orbit determination. The existence of the continuous body fixed small acceleration was assumed, and the acceleration was estimated along with the orbit from the ground observation data. Fig. 12 shows the O-C profile (from March 21 to 23) of the several cases of the determined orbits.
results of the two cases. “Cross” indicate the case where no acceleration was estimated, and “solid circle” indicate the case where acceleration was estimated. In the latter case, the existence of \( x, y, z \) components of the acceleration (in the satellite body coordinate system) are assumed and estimated. It is apparent that O-C of the latter case is much smaller than that of the former case, which indicates that continuous body fixed acceleration is likely to be acting on AKARI. Next, the compositions of the acceleration are investigated in detail. Fig. 12(b) shows the results of the two cases. “Cross” indicate the case where the existence of \( x, y, z \) components of the acceleration are assumed and estimated, and “solid circle” indicate the case where the existence of \( x, y \) components of the acceleration are only assumed and estimated. The result shows that O-C of the latter case is smaller than that of the former case, which indicates that the acceleration in \( xy \) plane (in the satellite body coordinate system) is likely to be acting on AKARI. It is true that, ideally, even in case that \( z \) component of the acceleration doesn’t exist, the former case simply estimates \( z \) component to be zero, and two cases yields essentially the same results. However, in practice, \( z \) component (i.e. radial component) of the acceleration is inherently insensitive to the orbit, and hard to be estimated accurately by way of the orbit determination. Fig. 13 shows the estimated \( x, y \) components of the acceleration. As a result of the investigation, the acceleration acted on AKARI was estimated at approximately \( 1.0 \times 10^{-6} \text{m/s}^2 \).

Assuming the following four conditions,
- The proportion \( \eta \) (less than 1) of the ejected Helium contribute to this effect.
- The temperature of Helium at ejection is 240K.
- The expansion of Helium is isotropic.
- The Helium molecules collide with the satellite wall as “perfectly elastic collision”.

the acceleration in \( +x \) (or \(+y\)) direction caused by this effect is estimated as

\[
a = 1.1 \times 10^{-6} \left( \frac{\eta}{0.6} \right) \left( \frac{\dot{m}}{1.7 \text{mg/s}} \right) \text{m/s}^2
\tag{1}
\]

where \( \dot{m} \) is the ejection rate of the gas Helium. (1) indicates that, assuming 0.6 for \( \eta \) and 1.7mg/s for \( \dot{m} \) (that is the actual ejection rate observed onboard), then, the acceleration caused by this effect is estimated as \( 1.1 \times 10^{-6} \text{m/s}^2 \), which approximately coincides with the value estimated by way of the orbit determination. The value 0.6 for \( \eta \) seems somewhat high, however, it was concluded that the acceleration was caused by this effect.

It was expected that, after the aperture lid is ejected, the ejection rate of the gas Helium was expected to be reduced to...
less than one third of the value above (i.e. the value when the aperture lid was still attached). This means that, after the aperture lid ejection, the rate of semi major axis increase, as well as the acceleration, is expected to be reduced to less than one third of the value observed then. Fig. 15 shows the prediction of the deviation from the sun synchronous condition (which is expressed as the transition of the angle between the right ascension of the sun and the ascending node of the orbit) and the time of eclipse, assuming that the semi major axis of the orbit would increase by the rate 45m/day. The time of eclipse in June 2007 shortens compared with the case of the rate 190m/day in Fig. 11, and it is regarded as acceptable level. As a result, it was concluded that the orbit rising problem would not be the obstacle for the aperture lid ejection operation.

After the aperture lid ejection, it was observed that the rate of semi major axis increase was reduced to the level we had predicted, and it was proved that the investigation was correct (Fig. 16).

4. Conclusion

AKARI is the first Japanese satellite dedicated to the infrared astronomy, which was successfully launched by M-V rocket from Kagoshima Space center on February 22, 2006. Reported in this paper is the initial phase AOCS operation of AKARI. Just after the launch, AKARI faced to a serious problem, "+y side panel problem". The fields of view of two (out of two) sun sensors are interfered by something and they were out of use in the subsequent AOCS operation. As other many satellites, the sun sensors has been planned to play important roles in AKARI’s AOCS operation. Firstly, they were to be used for sun acquisition at the very initial phase. The anomaly prevents us from carrying out the pre-planned sequence. However, the crisis was overcome with the appropriate ground support operation. Secondly, the sun sensors were to be used to watch the sun direction to keep the sun in appropriate direction even when the satellite falls into the safe mode. In order to achieve this function in the absence of the sun sensors, AOCS architecture was reconfigured so that the equivalent function is achieved by the remaining sensors. In addition, unexpected continuous orbit rising was observed in the operation. As a result of the investigation, the cause of the phenomenon was identified as the ejected gas Helium. Consequently, after one month’s delay from the preplanned schedule, the aperture lid of the cryostat has been successfully ejected on orbit and the scientific observation has been going on.

It was fortunate that the observed phenomenon was the orbit “rising”. If the observed phenomenon had been the orbit “falling”, it would have been more difficult to specify the cause of the phenomenon. There would have been more candidates of the cause, which include the unexpected large air drag related with "+y side panel problem".

Fig. 15 Prediction of Deviation from the Sun Synchronous Condition and Time of Eclipse (assuming 45m/day for increasing rate of semi major axis)

Fig. 16 Profile of Semi Major Axis after Aperture Lid Ejection