Development of Automatic Monitoring and Diagnostic System for Space Science Satellites

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ISACS-DOC (Intelligent SAtellite Control Software-DOCtor), which is automatic monitoring and diagnostic system for spacecraft, has been developed and operated at Institute of Space and Astronautical Science (ISAS) of Japan Aerospace Exploration Agency (JAXA). It aims to rapidly and accurately capture important changes and signals of anomaly during routine operations without the continuous presence of specialists. Three ISACS-DOC systems have been so far constructed for the features of deep or semi-deep space missions. Recently, ISAS launched three low-altitude earth orbiters in succession. Therefore, this paper presents overview and operation results of the newly developed monitoring and diagnostic systems for low-altitude earth orbiters different in various aspects from the deep space spacecraft targeted by the past ISACS-DOC systems.

I. Introduction

To satisfy the high-grade observation requirements of a scientific satellite, the number of devices per satellite is increasing, software functions are becoming complicated and enhanced, and the number of operating stations is also increasing with the enrichment of satellite operating facilities. To realize accurate and safe satellite operations, the following issues should be resolved.

- Each component has a function to detect and report an abnormality. Because of various abnormality reports, however, visual checks are substantially impossible.
- It is impossible to identify a true abnormality from multiple reports and determine an appropriate action in a limited time.
- It is not difficult to detect an abnormality in each component, but it is difficult to find the phenomenon of influence between components.
- An apparently true abnormality can be detected by a device but a general judgment must be made not only from abnormality information but also from multiple trend information. However, when there is a great volume of information, it is difficult to find and detect abnormal symptoms by human intuition.
- A trained expert may be able to find the signs of fault by experience and intuition, but an operator for regular operations cannot be expected to find such signs.

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Under these circumstances, a monitoring and diagnostic system for satellite operations is needed for flexible operations linking satellite operation planning, tracking control, and data processing. Since 1992, therefore, the Institute of Space and Astronautical Science of the Japan Aerospace Exploration Agency (ISAS/JAXA) has been conducting research and development on a ground system for monitoring and diagnosing the status of satellites using AI techniques. This system is called Intelligent Satellite Control Software-DOCtor (ISACS-DOC).[1–4] The purpose of ISACS-DOC is to accurately grasp serious changes and abnormality signs during regular operation without experts in the satellite control room to enhance the safety of satellite operations. For this purpose, information from the satellite to the ground facilities needs to be integrated and visualized. If the cause of an abnormality cannot be identified from detected signs, it is preferable to consult an expert by presenting the related information and contact address. If the cause can be identified with high reliability, it is preferable to present diagnostic results and solutions. ISACS-DOC can be positioned as a system to support monitoring by an operator in regular operation and to support diagnosis by an expert in abnormal operation.

At the same time, ISACS-DOC is considered to complement ordinary satellite control systems, from the general viewpoint of satellite control systems. Its main purpose is to improve the probability of abnormality recognition by post-launch tuning, trial monitoring and diagnosis. Therefore, the system should be independent of existing satellite control systems and should not affect their operations. Independence of existing facilities makes trial studies easy and more accurate. Moreover, the monitoring and diagnostic techniques verified by this system will contribute to the continuous improvement of satellite operation technology through their incorporation into the next satellite control systems.

So far, ISACS-DOC has been applied to the Geomagnetic Observation Satellite GEOTAIL (launched in 1992), Mars Explorer NOZOMI (launched in 1998), and sample-return probe HAYABUSA (launched in 2003). For GEOTAIL, the first ISACS-DOC system was constructed by using a diagnostic expert system construction tool (a packaged software). To date, ISACS-DOC systems for NOZOMI and HAYABUSA have also been developed and put into service.

Recently, ISAS launched three low-altitude earth orbiters in succession. Therefore, new-generation ISACS-DOC has been developed for two of them, AKARI and HINODE, which are low-altitude earth orbiters different in various aspects from the deep space spacecraft targeted by the past ISACS-DOC systems. There are certainly many issues to discuss about the monitoring and diagnostic system for low-altitude earth orbiters. Improvement items based on past experiences can also be considered as issues of the next-generation system. The new generation ISACS-DOC was developed and applied to the actual operation for AKARI and HINODE. This paper reports the overview of the ISACS-DOC system for earth orbiter AKARI and HINODE and their operation results.

II. Low-altitude earth orbiters AKARI[5] and HINODE[6]

AKARI(ASTRO-F) is the second space mission for infrared astronomy in Japan. It was launched by M-V rocket No. 8 on February 22, 2006 from Uchinoura Space Center. It is placed in a sun-synchronous polar orbit of 745 km and given a nickname of "AKARI", which means a "light" in Japanese. The AKARI mission is an ambitious plan to make an all-sky survey with much better sensitivity, spatial resolution and wider wavelength coverage than IRAS (Infrared Astronomical Satellite, launched in 1983 by the United Kingdom, the United States, and the Netherlands). AKARI has a 68.5cm telescope cooled down to 6K, and will observe in the wavelength range from 1.7 (near-infrared) to 180 (far-infrared) micron. By these equipments, AKARI will make a second generation survey which meets current astronomer's expectations. There are a large variety of scientific targets which will be investigated by AKARI as follows, 1) to understand the formation and evolution of galaxies, 2) to inquire into the formation process of stars and planetary systems. In order to accomplish these aims, AKARI performs the following observations. 1) an unbiased all-sky survey at wavelengths from 50 to 180 microns, and 2) high sensitivity imaging and spectroscopic observations covering more than several tens of square degrees at wavelengths from 1.7 to 180 microns.

HINODE(SOLAR-B) is the third solar observation satellite in Japan. It was launched by M-V rocket No. 7 on September 23, 2006 from Uchinoura Space Center. HINODE has three advanced solar telescopes, SOT, XRT and EIS. The solar optical telescope (SOT) has an unprecedented 0.2 arcsec resolution for the observation of solar magnetic fields. It would resolve a feature with the size of 50cm, if it observed the Earth. The X-ray telescope (XRT) has a resolution of three times as high as YOHKOH,which is the second solar observation satellite in Japan. The EUV imaging spectrometer (EIS) has sensitivity ten times as high as the

ESA SOHO instrument. These X-ray and EUV telescopes would reveal the heating mechanism and dynamics of the active solar corona. With this suite of telescopes, HINODE can address the following key questions in solar physics, 1) Why does a hot corona exist above the cool atmosphere, 2) What drives explosive events such as solar flares and 3) What creates the Sun's magnetic fields.

Figure 1 shows AKARI and HINODE which are ready to be loaded onto the M-V rocket.

(a) AKARI (b) HINODE

Figure 1. Low-altitude earth orbiters AKARI and HINODE

III. Main target of new ISACS-DOC for AKARI and HINODE

AKARI and HINODE are a low-altitude earth orbiter different in various aspects from the deep space spacecraft targeted by the past ISACS-DOC systems. The greatest difference in terms of ISACS-DOC for AKARI and HINODE is the requirement for high-speed data processing. This is because of the short visible time (for example, deep space spacecraft HAYABUSA: 8 hours, AKARI: 10 min/pass and 4 passes/day) and high transfer rate of telemetry data (HAYABUSA: 16 Kbps, AKARI: 4 Mbps). In other words, a large volume of data needs to be processed in a short time. For high-speed data processing, it is necessary to enhance the system processing performance, to set monitor rules strictly, and to set priorities. Therefore, the first purpose of new ISACS-DOC is to establish monitoring and diagnostic technology for low-altitude earth orbiters.

Knowledge collection and production vital to this system are expected to be more efficient. Therefore, the second purpose is to develop framework of knowledge collection, which consists of knowledge templates about science satellites by utilizing the experiences so far and support system to build knowledge base. Many knowledge bases were previously collected almost manually by experts and those with experience, and then incorporated into systems. This is expected to be automated to some extent. Therefore, we arranged the knowledge already collected, and summarized common knowledge into templates to have many diagnostic rules incorporated into systems automatically. These templates and support system to build the knowledge base are realized by spreadsheet files and macro features of spreadsheet software, respectively.

IV. Features of new ISACS-DOC

Figure 2 shows operation image of ISACS-DOC. ISACS-DOC system gets real time telemetry data and

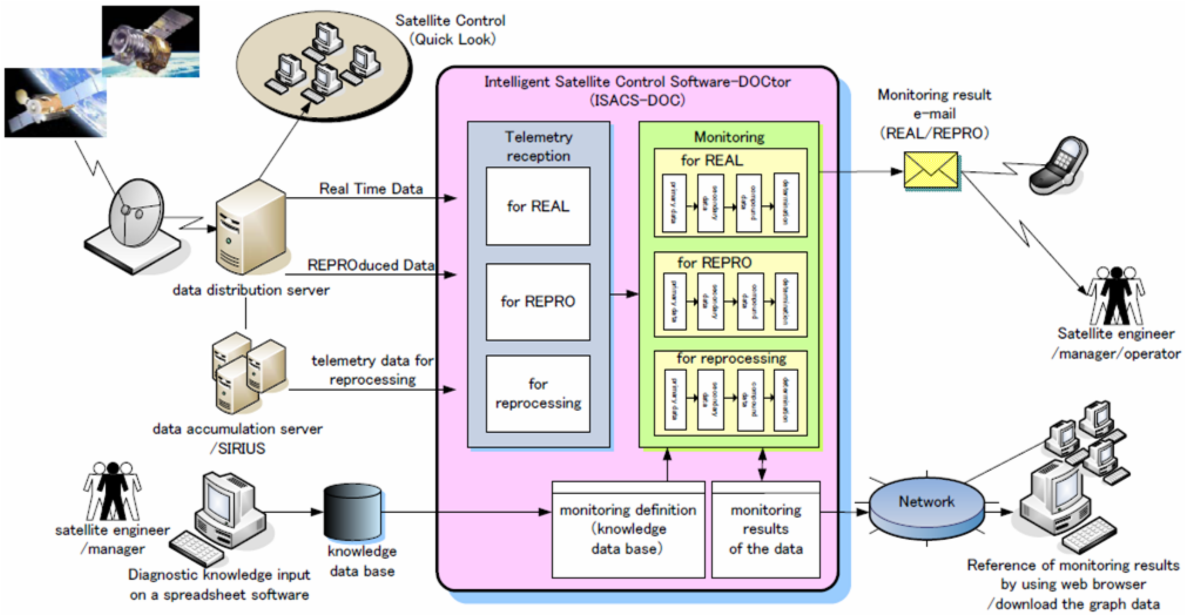


Figure 2. Operation image of ISACS-DOC for AKARI and HINODE

reproduced telemetry data, from data distribution server, and monitors and diagnoses both data (real time and reproduced) at the same time. Diagnosed results are displayed in a monitor and are sent by e-mail. ISACS-DOC consists of following 6 functions.

1. Import : the system imports the knowledge base and telemetry definition database and extracts telemetry entry, which are required in monitoring and diagnosing.

2. Telemetry reception : the system receives telemetry data in real time, decomposes them to each telemetry entry, extracts status values, converts to physical values and finally creates primary data, according to the telemetry definition database.

3. Monitoring data creation : the system creates monitoring data which are necessary for monitoring and diagnosing, based on the knowledge base. A filtering procedure and limit check are applied to primary data, creating secondary data. Complex data are created from multiple data: secondary data and complex data, as needed.

4. Monitoring and diagnosing : the system monitors and diagnoses according to the definition of knowledge base.

5. Display : monitored and diagnosed results are shown through a HTTP server.

6. Notification by e-mail : monitored and diagnosed results are notified by the e-mail after the spacecraft operation or monitoring and diagnosing of reproduced telemetry data are completed.

ISACS-DOC can automatically monitor and diagnose reproduced telemetry data which are reproduced from the on-board data-recorder and are sorted according to their TI-time (time by the Time Indicator on spacecraft) as well as real time telemetry data. Both data processing are independent and they can be executed at the same time when reproduced telemetry data and real time telemetry data are received. ISACS-DOC can also re-diagnose any past data with the newest knowledge base.

IV.A. Data processing

Figure 3 shows schematic view of the data processing. ISACS-DOC has several parameters to control data processing. They are cycle of monitoring data creation, cycle of conducting monitoring and diagnosing, and data collecting period. ISACS-DOC can freely setup these values, according to features of monitoring data, and monitoring and diagnostic rules.

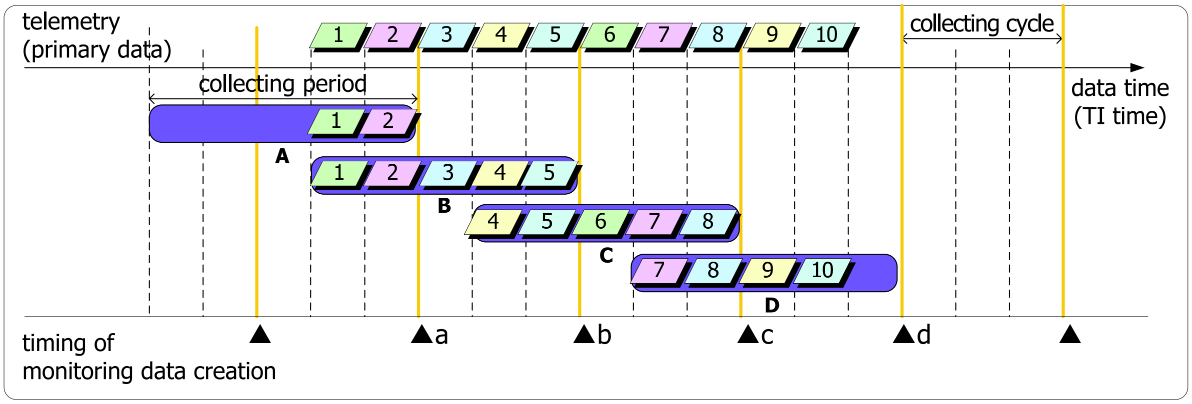


Figure 3. Data processing timing

Telemetry data rarely have garbled data which are caused by one-bit errors etc.. The garbled data causes incorrect alerts which decrease the reliance on the system. Therefore, a data filtering technique is used in the ISACS-DOC. The filter deletes incorrect values in primary data and creates appropriate data as secondary data in order to realize well-established monitoring and diagnosing. Figure 4 shows filtering process to create secondary data. Secondary data consists of central values which are calculated every collecting cycle. A central value is calculated for each collecting period from the collected primary data according to the filtering algorithm.

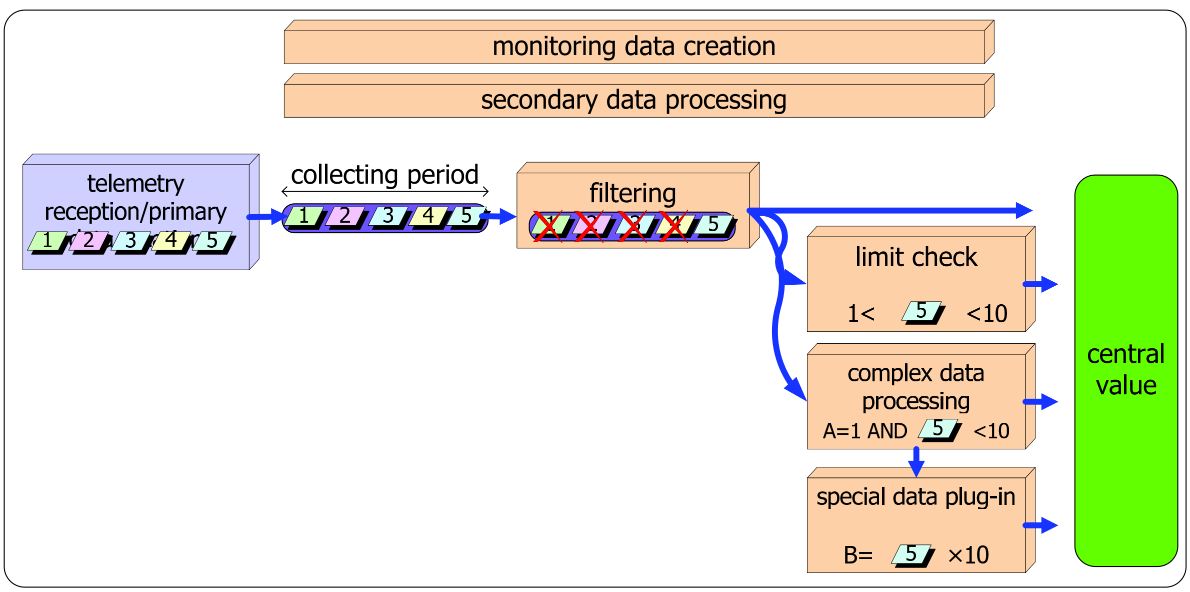


Figure 4. Secondary data processing (filtering)

Table 1 shows a list of filters which are implemented in the system. In general, the *average2*, an average of collected data except maximum and minimum values, is used for analog data. The *majority*, a mode value of collected data, is used for status data.

Complex data are created from following multiple data: secondary data and complex data. By using these data, ISACS-DOC realizes complex monitoring and diagnosing. The boundary value of the limit check can change according to the current value of specified data. The system can detect continued anomaly by

Table 1. **Filters for data processing**

Name	Description	data type
head	the oldest data among collected data	analog/status
end	the newest data among collected data	analog/status
maximum	the maximum value of collected data	analog
minimum	the minimum value of collected data	analog
majority	a mode value among collected data	status
identity	a value when all data are identical	analog/status
average1	a simple average of collected data	analog
average2	an average of collected data except maximum and minimum values	analog
average3	an average of collected data except a specified range of data	analog
average4	an average of collected data except maximum, minimum and specified values	analog
extraction	extract a specified value	status

knowing starting time and ending time of specified status. (ex. it should be anomaly if a calibration light source continues to be ON more than five minutes.) Moreover, the system has calculating expression in a free format as a user intrinsic function as follows, 1) calculation of physical value (for example, electrical power from current and voltage of electricity), 2) predicted value (ex. tank pressure calculation by Boyle-Charle's law), 3) reference of past data (ex. count-up of counters), 4) comparison between expectancy and actual showing (ex. difference or ratio between them), and 5) historical trend analysis.

IV.B. Notification

Monitored and diagnosed results are shown on a display. No dedicated client software is required to check these results because a Web based interface is used to show them. Users can check the results in anywhere by commonly used Web browser through the network. Figure 5 shows the main window of ISACS-DOC. Detected anomalies are listed in the main part of the window, which is the most important region for ISACS-DOC users. Each listed anomaly is linked to another window (Fig. 6) which shows detailed informations: 1) current values of the anomaly data, 2) conditions of anomaly detection, 3) setting values of limit checks, 4) time series plots of not only the anomaly data but also the related other data, which provides valuable clues to understanding of the circumstances, and 5) messages of anomaly descriptions and the way to response. In the left side of the window, there is a list menu for all monitoring rules, which show current status of monitoring data regardless of whether an anomaly is detected. Each list in the menu is also linked to the detailed description window.

In order to grasp the trends or details of the data, ISACS-DOC has an offline monitor and the users can get any period of specified data, which are displayed in the trend graph. Figure 7 shows the offline monitor. In the offline monitor, users can enlarge the specified region of the trend graph and get the current value by pointing.

Monitored and diagnosed results are also notified by e-mail. Users can get the results in anywhere, even by mobile-phone text-messaging. Usually, spacecraft consist of several subsystems and each subsystem has its personnel, which wants to get only related monitored and diagnosed results. Therefore, ISACS-DOC has a function which can clip part of the monitored and diagnosed results according to the definition of the each subsystem and can send just enough informations to appropriate subsystem personnel.

IV.C. Watchdog of ISACS-DOC itself

The watchdog of ISACS-DOC itself is important in this kind of automatic monitoring system. ISACS-DOC has three kinds of process, 1) a monitoring and diagnosing process for real time telemetry data, 2) a monitoring and diagnosing process for reproduced data, and 3) a control process. The watchdog of ISACS-

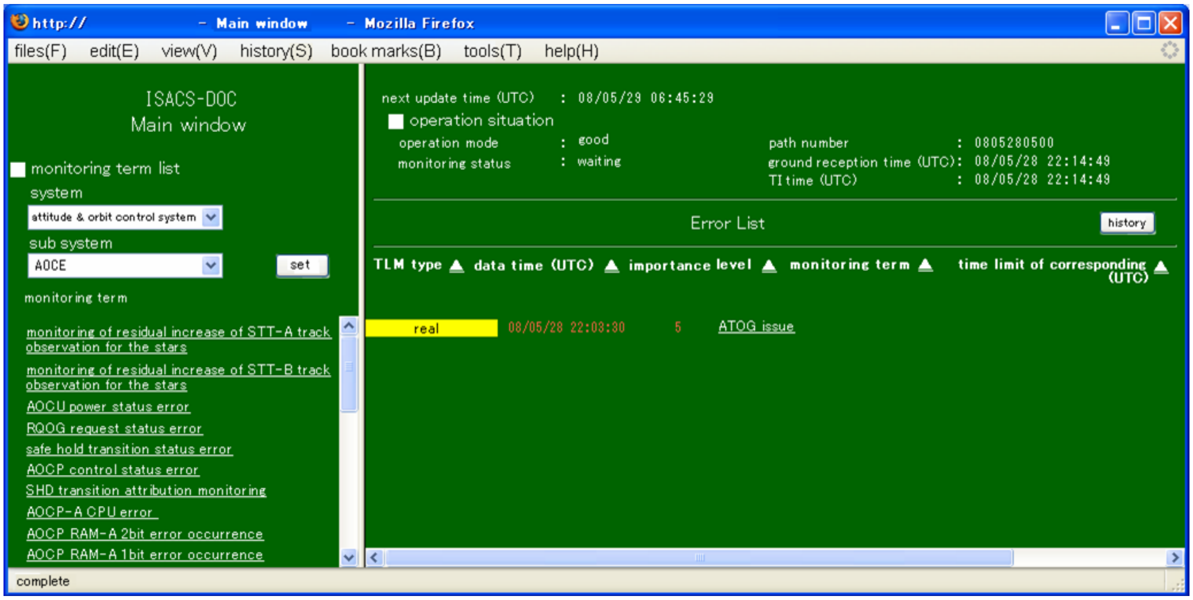


Figure 5. Main window of ISACS-DOC for AKARI

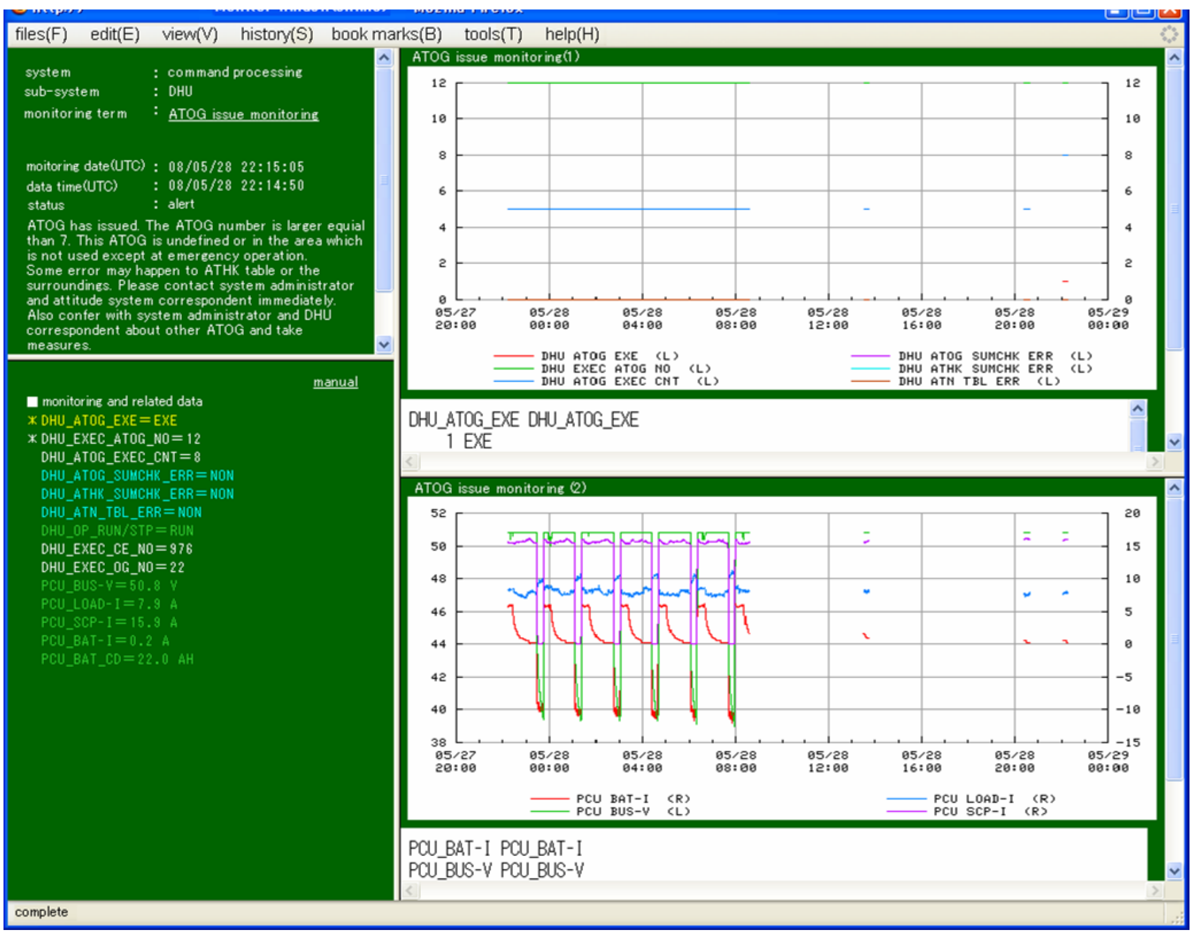


Figure 6. A detailed description window which shows mode informations

DOC checks every 30 minutes whether three processes are alive or not. If one of the process is found to be dead, it sends DOC-error e-mail every 30 minutes until the error is resolved. If all three processes work, it

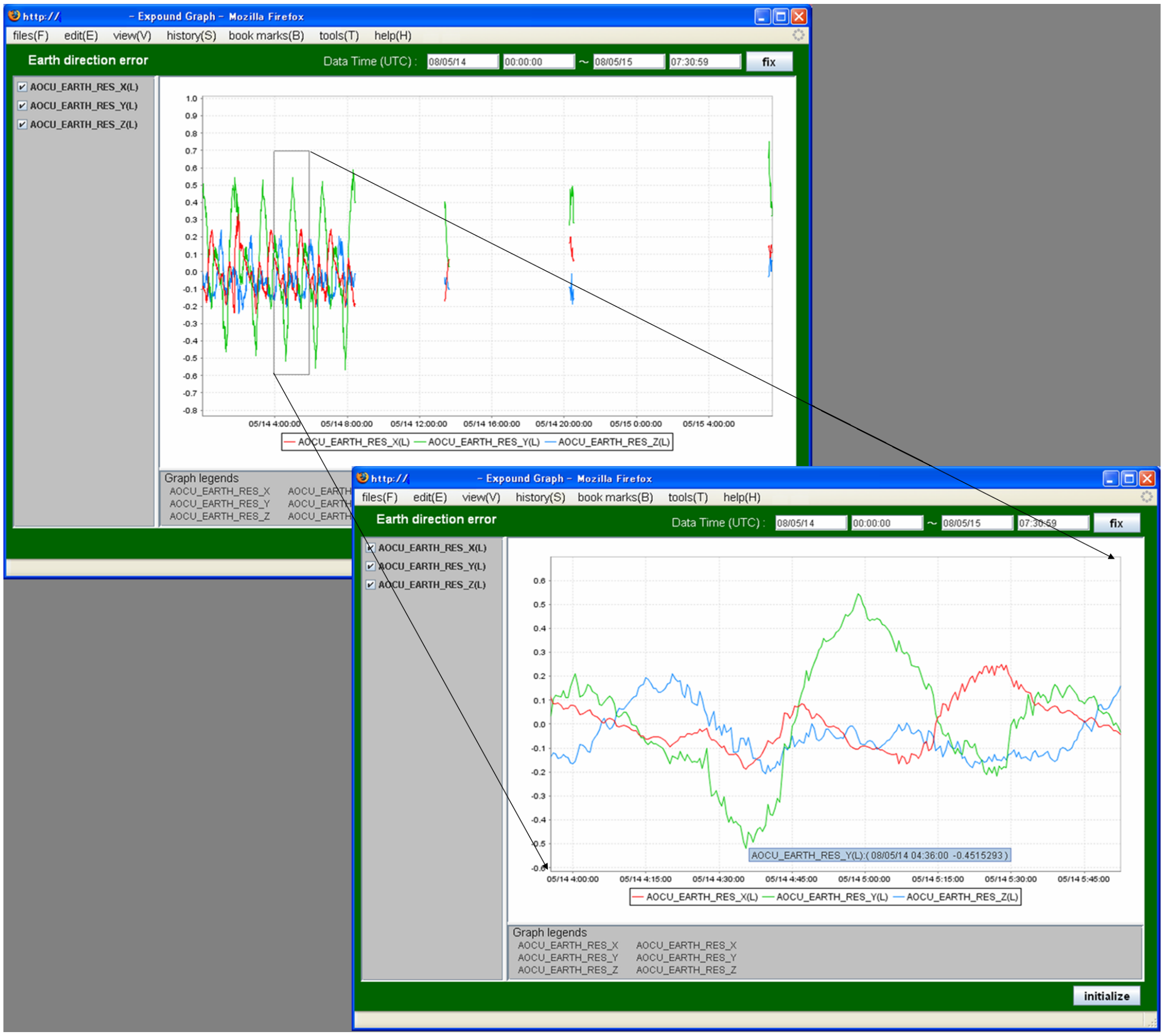


Figure 7. Offline monitor

sends DOC-alive e-mail once a day. The watchdog e-mails are sent to the member of the satellite project team as well as to ISACS-DOC developers.

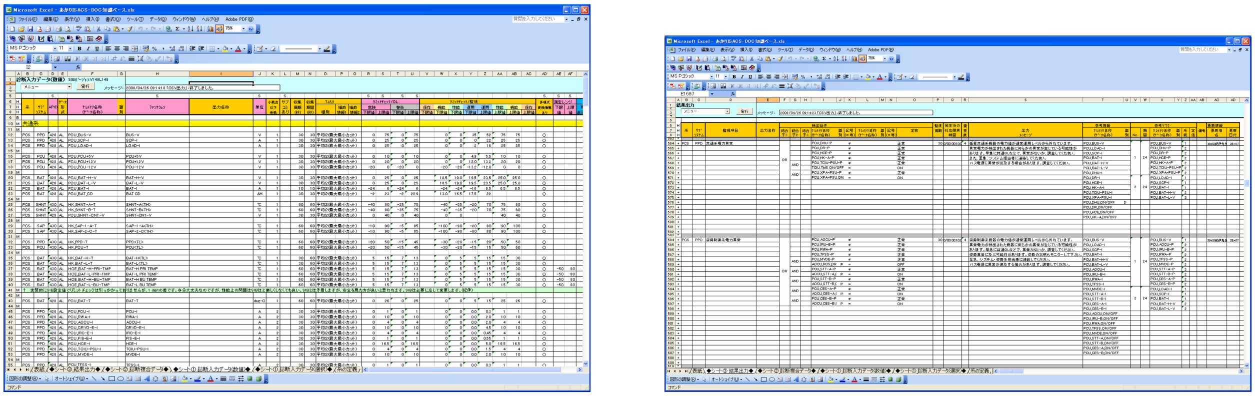
IV.D. Knowledge base

The framework of knowledge collection was developed, which consists of knowledge templates about science satellites by utilizing the experiences so far, and support system to build the knowledge base. The framework is constructed by using a spreadsheet software package, and collected knowledge is described in templates of the following three kinds of spreadsheets. Figure 8 shows an example of the spreadsheets.

1. Diagnostic input data (status and analog data) : input data which are necessary for monitoring and diagnosing, are defined in this sheet. For example, telemetry name, limit check values, collecting period and creation cycle of data, filtering type and valid/invalid condition.

2. Complex data : new data which are calculated from multiple data, are defined in this sheet.

3. Monitoring and diagnosing definition : monitoring and diagnosing rules are defined in this sheet. Each entry has conditions of anomaly detection, monitoring cycle, importance level, time limit for response. It has also the specification of data which are used to draw a graph showing time variation of data, the configuration of the graph, output messages like anomaly descriptions and the way to response. They are displayed in the detail description window.



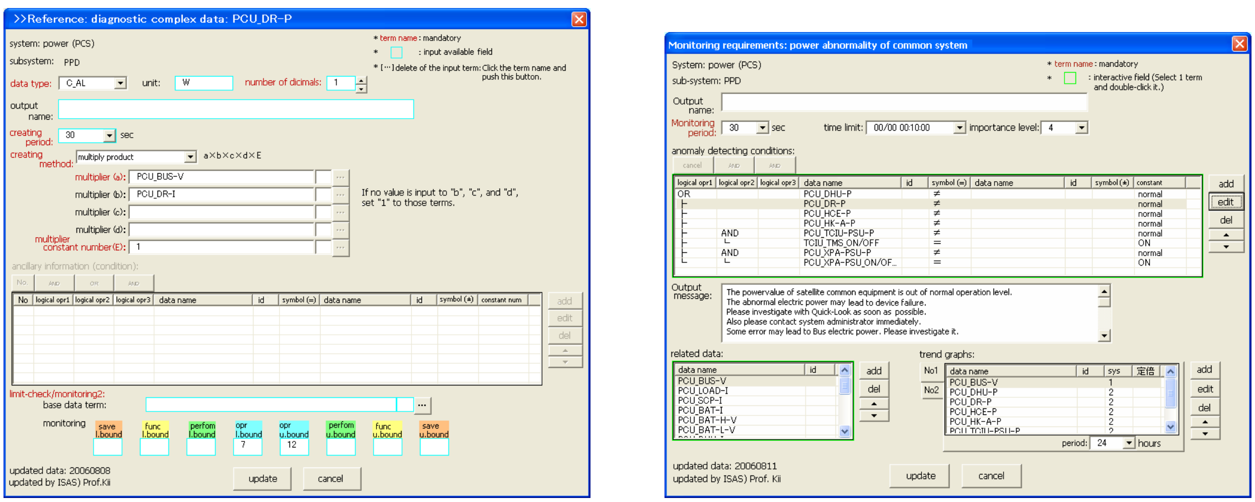
(a) Diagnostic input data

(b) Monitoring and diagnosing definition

Figure 8. Knowledge base described in spreadsheets

The knowledge base, which is described in the spreadsheets, becomes more easily viewable than previous one. The knowledge already collected is arranged and summarized as common knowledge into templates to have many diagnostic rules for spacecraft. These templates help to advance the knowledge base which can be used for monitoring and diagnostic system for future spacecraft. The knowledge base is converted to CSV formatted files, which are directly imported by ISACS-DOC.

The support system is required to build the knowledge base, decreasing input loading of users and having a function to check consistency of the knowledge base. Especially in the operating phase of satellite, it is expected to keep up the knowledge base more timely and efficiently following the status change of the satellite operation even by the project team of the satellite, who are not familiar with ISACS-DOC. For this purpose, a GUI-based editor was developed to make and maintain the knowledge base easily and efficiently. Figure 9 shows sample screen shots of the GUI-based editor.



(a) Complex data definition

(b) Monitoring and diagnosing definition

Figure 9. GUI-based editor for knowledge base

In the past ISACS-DOC, only a few people which are familiar with ISACS-DOC can input or change the knowledge base and it decreases the convenience of the system. This editor is designed for experts who are not familiar with ISACS-DOC but familiar with the satellite to maintain the knowledge base running on ISACS-DOC timely and easily. It has a kind of wizard to input data, a pull-down menu, which allows users to select a suitable input value, and data association by link connection. The security features are also added to the editor, having a password authentication function. Only the authorized users can edit the authorized knowledge base. The authentication feature can be applied to each knowledge base of each subsystem. The editor automatically imports the telemetry definition database. Several values which are defined in the telemetry definition database, are used as default values or are displayed as reference values for data input.

Moreover, following functions are realized in order to ensure consistency of the knowledge base, format check (required item, fixed word, letter type and number of letters) and consistency check (duplication of entry, magnitude relation of limit check values, relation between collecting cycle and collecting period of data, conditional expression for anomaly detection, and lack of required data for diagnosing). The editor helps to maintain as well as to build the knowledge base more certainly, efficiently and safely. The editor has been used in both AKARI and HINODE project teams to maintain the knowledge base.

It is distinctly important for ISACS-DOC to collect diagnostics knowledge, to build and maintain a knowledge base at a useful and high level. Many knowledge bases were previously collected manually by experts and those with experience, and then incorporated into ISACS-DOCs. Now, the knowledge templates about scientific satellites are prepared by utilizing those experiences so far. We analyze and arrange the knowledge base already collected, to summarize common knowledge into templates allowing the incorporation of many diagnostic rules into systems. The knowledge template is comprised of an instruction manual and a sample knowledge base files. The sample knowledge base is used as the basis of the knowledge base and the instruction manual is used as a guide line to build the knowledge base for future spacecraft.

V. Operating results of ISACS-DOC

ISACS-DOC for AKARI and HINODE were developed and applied to the actual operation, which helps daily operation of both satellites.

V.A. Daily operation status

In AKARI operation, ISACS-DOC monitors and diagnoses the real and reproduced telemetry data five or six times a day. The number of visible real-time path is three times a day and the reproduced telemetry data sets are two or three times a day. In HINODE operation, ISACS-DOC monitors and diagnoses the real and reproduced telemetry data more than fifty times a day. The number of visible real-time path is sixteen times a day and the reproduced telemetry data sets are more than thirty six times a day.

Through the daily operation of two ISACS-DOCs, following things are evaluated. Detection of anomaly is of course important. Moreover, daily message without any anomaly provides the sense of security. The framework of the knowledge templates in ISACS-DOC is effective. The personnel of the satellite project team, who are not familiar with ISACS-DOC, can maintain the knowledge base timely and easily by using the GUI-based editor.

V.B. Detect the first sign of the on-board coolant boil-off for AKARI

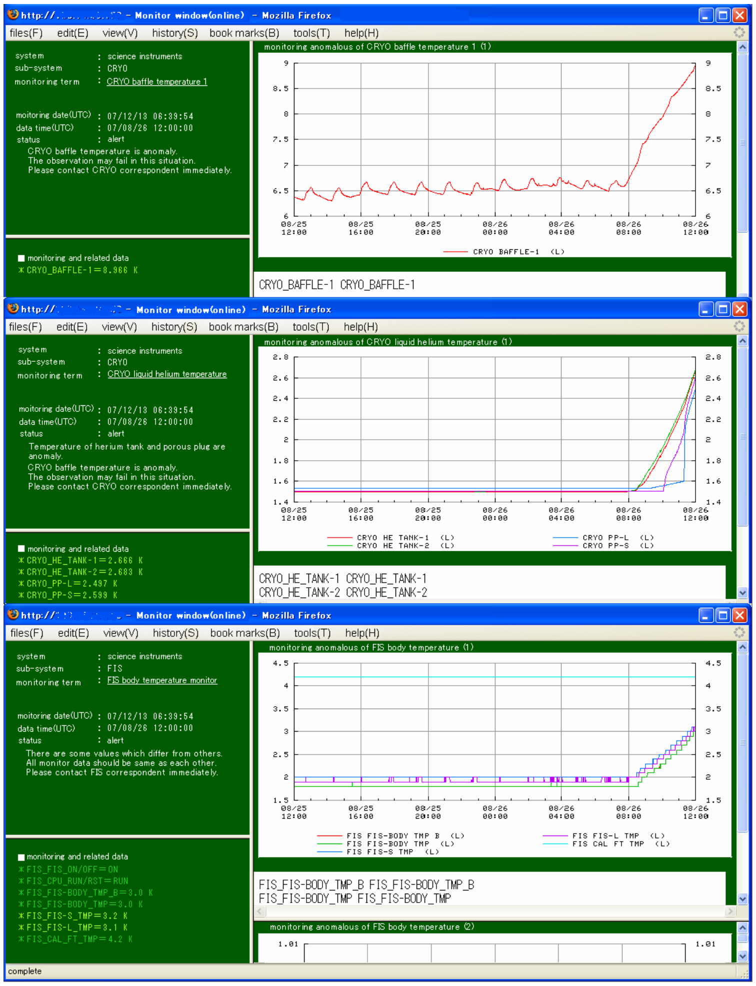
The far- and mid-infrared all-sky survey, which is an main subject of AKARI, had been successfully performed in the expected time frame of about 500 days, and finished at 08:33 (UT) on August 26, 2007, due to the boil-off of the on-board coolant liquid helium. Since then, AKARI changed into the observation mode with the near-infrared camera, which operates at a warmer temperature maintained only by the mechanical coolers. ISACS-DOC for AKARI detected the first sign of the rapid temperature increase of the cryogenics which would indicate the boil-off of the on-board liquid helium. The sign was obtained at a down-link station of the Svalbard Ground Station, where data could not be monitored in real time. ISACS-DOC immediately notified anomaly to experts in AKARI project team by e-mail.

Figure 10 shows the e-mail and the display monitor which notify the anomaly of the temperature increase. The quick alert helped to take rapid decision for the next operation within 2 hours after the notification, and implement the immediate countermeasure at the next command-operation contact.

VI. Conclusions

The overview of the new monitoring and diagnostic system for AKARI and HINODE, was presented. It was the first attempt to develop the monitoring and diagnostic system for low-altitude earth orbiters. Its effectiveness has been proved through the daily operation. Further efforts will continue to enhance the system. ISACS-DOC will continue to assist the safe operation of AKARI and HINODE until the end of the both satellite missions.

The ISACS-DOC, described in this paper, becomes a future basis of the monitoring and diagnostic



(a) Detection of the temperature increase

Send Data: 2007/8/26 Sun. 22:56
Subject: ASTRO-F ISACS-DOC Summary Error (REPRO)

Monitoring results for re-produced telemetry data

[Operational Information]

Path Number : 0708262500
Reception Station : SVAL
Telemetry Type : REP
Start Time : 2007/08/26 12:28:00
End Time : 2007/08/26 12:42:20

[Monitoring Results]

Temperature anomaly of FIS Structure (FIS)

Monitoring cycle : 30 sec.
Impotance level : 3
Time limit for response : 2007/08/26 12:38:30

Occurence time of anomaly
Monitoring date :2007/08/26 13:55:59
Data date :2007/08/26 12:28:30
Monitored and related data in the anomaly
* FIS_FIS_ON/OFF=ON
* FIS_CPU_RUN/RST=RUN
* FIS_FIS-BODY_TMP_B=3.2K(Lv.0)
(| | | |1.5|4.0| | | |)
(skip...)

Temperature anomaly of liquid helium in CRYO (CRYO)

Monitoring cycle : 60 sec.
Impotance level : 3
Time limit for response : 2007/08/26 12:39:00
(skip...)

Temperature anomaly of CRYO baffle #1 (CRYO)

Monitoring cycle : 60 sec.
Impotance level : 3
Time limit for response : 2007/08/26 13:29:00

Occurence time of anomaly
Monitoring date :2007/08/26 13:56:00
Data date :2007/08/26 12:29:00
Monitored and related data in the anomaly
* CRYO_BAFFLE-1=9.163K(Lv.1)
(| | | |5.500|7.800| | | |)

Period

(b) E-mail notifying the detection

Figure 10. The detection of the coolant boil-off of the on-boad liquid helium

system at ISAS/JAXA. At the same time, the experiences obtained from the development and operation of ISACS-DOC are applied to the development of a newly planed science satellite control system.

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