

# IN-ORBIT PERFORMANCE OF "ASCA" SATELLITE ATTITUDE CONTROL SYSTEM

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Japan's X-ray astronomy satellite ASCA (ASTRO-D) was launched on February 20, 1993. The main mission of the satellite is to observe the X-ray images of extended celestial objects by using high throughput on-board X-ray telescope. The telescope's requirement on attitude pointing control is 1 arcmin and after the fact accuracy of the pointing attitude of 0.3 arcmin is required. The attitude control system (ACS), which is based on a bias momentum scheme, adopts unique designs in initial attitude acquisition, maneuver scheme during mission, the angular momentum management, and the safe-hold attitude control. In this paper, these ACS design features are briefly described and its flight performances are shown, by focussing on the flight experiences gained through one year satellite operation.

## INTRODUCTION

ASTRO-D, the fourth X-ray astronomy satellite of the Institute of Space and Astronautical Science (ISAS), was launched on February 20, 1993 by a M-3S II launch vehicle from Kagoshima Space Center (KSC), into a near circular orbit of a 622 Km apogee 524 Km perigee altitude and 31.1 degs. inclination. ASTRO-D in orbit was named ASCA, which means "a mythological Japanese bird", and also an acronym of "Advanced Satellite for Cosmology and Astrophysics". ASCA is equipped with a high-throughput X-ray telescope with a large effective area over a wide X-ray energy range. The telescope system comprises three types of mission instruments: nested thin-foil X-ray mirrors (XRT), CCD cameras named "Solid state Imaging Spectrometers (SIS)", and image gas scintillation counters, or "Gas Imaging Spectrometers (GIS)". Four identical mirrors of XRT are mounted on the top of the extendible optical bench (EOB), while the focal plane instruments, two units of CCD camera

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and two units of imaging gas scintillation counter, are placed on the base plate. The focal length is 3.5 m. SIS observes the spectroscopic images of the X-ray objects, aiming especially at the research of the X-ray emission and absorption lines over 0.2 keV. GIS is in charge of image observations at higher energy part of 2-12 keV.

The outline drawing of ASCA mission phase configuration with solar paddles and X-ray telescope deployed is shown in Fig.1. Total satellite weight is about 462 Kg. The electrical power available from the solar paddles at the beginning of life(BOL) is 617 watts.

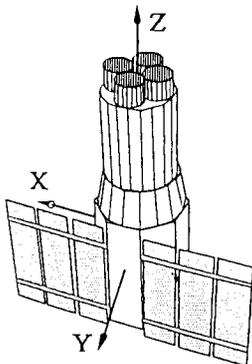


Fig.1 Outline Drawing of ASCA

Precision pointing control of ASCA attitude is required from the X-ray telescope to obtain high quality X-ray images [1]. High speed large angle attitude maneuver between the observations is also requested for efficient in-orbit observations. These requirements on the attitude control system are shown in Table 2.

Beside the mission requirements, there are two points to be considered in designing the ACS of ASCA. One is the satellite injection at a high spin-rate by M-3S II rocket, of which final stage is solid motor. The other is the design of "safe-hold attitude" control to save additional cost and weight of the ACS system as much as possible, while fully guaranteeing the electrically and thermally safe conditions at contingencies. Based on these considerations, the attitude control system using four biased momentum wheels is adopted.

Being in-orbit nearly one year operation, ASCA has been contributing much to the research of cosmic X-ray sources. From the stand point of the ACS, it also has provided many experiences in orbit. In this paper, mainly in orbit experiences of the ASCA ACS will be described. First, the ACS is presented briefly, then ACS performance in orbit will follow. Finally, the following in-orbit issues and experiences by the ACS are discussed.

- (1) Robustness of on-board attitude determination system
- (2) Pointing anomaly due to thermal distortion of the satellite structure
- (3) Unexpected transition to the safe-hold attitude
- (4) Anomalies during attitude maneuver due to gyro degradation

## ATTITUDE CONTROL SYSTEM DESCRIPTION

The attitude control system has three major control functions: the spin-phase attitude control, the mission phase attitude control, and the momentum transfer control at the transition from the spin-phase to mission-phase. Those functions except for the mission phase are implemented by a simple hard-wired logic without resorting to the on-board computer. The mission phase attitude control is made up of the functions of an attitude determination, pointing control, attitude change maneuver, and angular momentum management. All of these functions are realized by the on-board software logic. In addition to these functions the safe-hold attitude control function is provided in case of system contingencies.

The block diagram of the attitude control system of the ASCA is shown in Fig. 2. The attitude controller is made up of an attitude control electronics (ACE) and an attitude control processor (ACP). The ACP is provided with queued redundancy by two computer units, each containing a radiation hardened 16-bits gate array microprocessor.

The inertial reference unit (IRU-SA) contains four rate integrating gyros, three of which make up an orthogonal reference triad, while the fourth skewed gyro provides a queued redundancy. To consolidate the IRU system against the in-orbit troubles one more gyro unit (IRU-SB), which has only one gyro sensor, is added for the additional redundancy. The input axes of the IRU-SA gyro sensors (X, Y, Z gyro) are aligned to X, Y, Z and skewed gyro (S1 gyro) with  $\langle 1, 1, 1 \rangle$  direction. The input axis of the S2 gyro of the unit IRU-SB is aligned to  $\langle -0.674, 0.671, 0.308 \rangle$  direction. A pair of star trackers is aboard ASCA. Their boresights are directed to  $\langle -1, -1, 0 \rangle$  and  $\langle 1, -1, 0 \rangle$  in the body fixed coordinate. Each of star trackers uses a two-dimensional CCD and contains a microprocessor for the star data processing and mode control. Each tracker with the field of view (FOV) of about 7 degs. by 7 degs., can detect stars up to 6-th visual magnitude with the angular accuracy of about 5 arc-sec., and can track three stars simultaneously. The trackers also have a star mapping capability to be used for ground-based star identification and attitude determination. Two dimensional fine sun-sensor (TDSS) using a pair of linear arrays of CCD's as the sun position detection device, measures the sun angles in the body-fixed X-Y and Y-Z planes. The sensor provides the attitude information referring to the Sun with an accuracy of 0.05 degs.. The sensor has the square FOV of 100 degs. by 100 degs.. The magnetometer (GAS: Geomagnetic Aspect Sensor) is the ring-core fluxgate type, and senses three field components along the body coordinate X, Y, and Z axes. The sensing accuracy is better than 100 nT. A pair of spin type sun sensors, having angular resolution of 1 deg., has a fan beam shaped FOV subtending 120 degs. and laying in the satellite Y-Z plane. Four momentum wheels (MW-A, B, C, D) are symmetrically tilt-arranged around the satellite Y-axis. These wheels are operated at 2000 rpm of nominal bias speed (it corresponds to 7.5 Nms), and the wheel system has the capability to manage the satellite angular momentum from 5.5 Nms to 12 Nms. Three magnetic torquers are arranged along X, Y and Z axes (MTQ-X, MTQ-Y, MTQ-Z respectively). Each torquer has the capability of generating about 70 ATm<sup>2</sup> magnetic dipole moment.

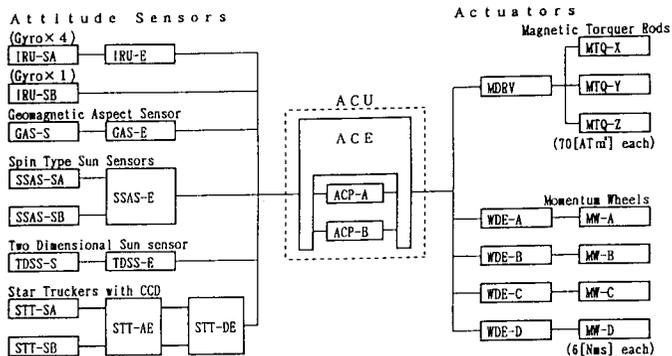


Fig. 2 Block Diagram of ASCA Attitude Control System

### Spin-phase Attitude Control

At orbit injection the satellite has a high spin-rate of 132 rpm around Z axis. To remove this angular momentum (leaving only small amount for the bias momentum in the wheel system) a yo-yo despinner is used for the first rough adjustment. Though the yo-yo despinner is a simple and light-weight device, it has poor capability of adjusting the spin-rate.

Based on the yo-yo despin dynamics analysis, initial spin reduction was planned to be conducted by two steps, the large and rough despin from 132 rpm to 7 rpm by the yo-yo despinner and further despin from 7 rpm to 0.9 rpm by magnetic torquers. After the yo-yo despin, the satellite needs to be kept in the spinning state of 7 rpm for several days with the solar paddles closed, with the satellite's shape being a nutationally astable long cylinder. Hence, during this period an active nutation dumping control by magnetic torquing is equipped, beside the fine angular momentum adjustment also by magnetic torquing.

The spin-phase attitude control system is composed of two segments; an on-board control system and ground support system [3]. Ground support system is described in the next section. The on-board magnetic attitude control system comprises a geomagnetometer, three magnetic torquers, and a control logic circuit. The functions of the on-board spin-phase attitude control system are as follows.

- (1) Spin-rate control (open loop control).
- (2) Spin-direction control (open loop control).
- (3) Active nutation control (closed loop control).
- (4) Sun acquisition control (closed loop control).

In the first above two control scheme (1) and (2), an open-loop control is adopted by the reasons of a simple hardware implementation and flexible operation in the critical initial period. As the satellite configuration is spin-astable during the initial spin around Z axis, the active nutation control (3) is required to keep an attitude stability,

in which a magnetometer is adopted as a nutation sensor because of its low power consumption. In the sun acquisition control mode (4), the satellite body spins very slowly and only the two of four wheels run at nominal speed. This slow spin around the Y-axis enables the sun pointing of this axis by means of a quite simple magnetic control logic using the geomagnetometer, spin type sun sensor, and the magnetic torquer MTQ-Y.

### Mission phase Attitude Control

The attitude determination system at the mission phase is depicted in Fig.3. The two star trackers combined with an inertial reference unit make up the attitude sensing system. In gyro data processing section, the incremental angular pulse outputs from the IRU are sampled and then drift- and alignment-compensated every 125 msec. The attitude propagation section integrates these data to obtain the satellite attitude employing the small Euler angle approximation for the outputs from the gyro data processing section. The attitude is expressed in quaternion form as the attitude calculation error remains small even for large angle attitude maneuver. The STT data processing section computes the direction vectors of up to three stars for each star tracker in the body-fixed frame. This processing is performed every 32 secs. A prior coarse satellite attitude and the star catalogue are up-linked to the ACP. The on-board software automatically identifies the stars, and then updates both attitude and gyro rate biases using a typical Kalman filtering technique. Normally two or three star tracking are enough for the required precision of the on-board attitude determination.

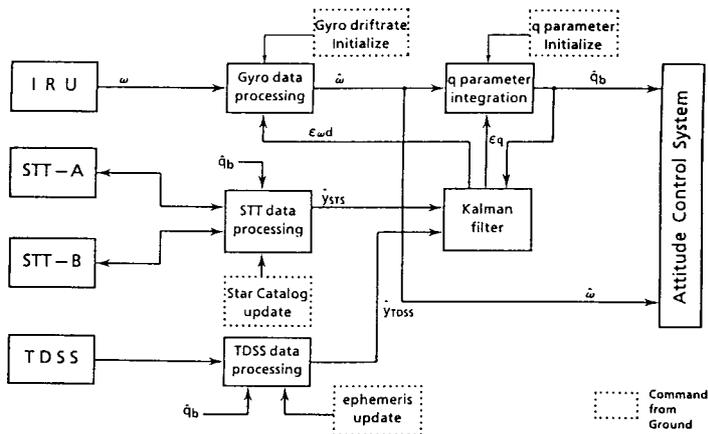


Fig. 3 Attitude Determination System

The block diagram of the mission phase attitude control for the pointing and maneuver is shown in Fig.4. The pointing control system employs the gyros as the primary sensor to stabilize the satellite body in the inertial space. The mission phase attitude pointing control system comprizes both attitude pointing and attitude maneuver controls.

The controller has two modes: fine mode for the attitude pointing and coarse mode for the attitude maneuver. To achieve the fine pointing performance, the fine mode adopts the PD-controller, while the coarse mode uses D-controller for the purpose of the adequate maneuver speed.

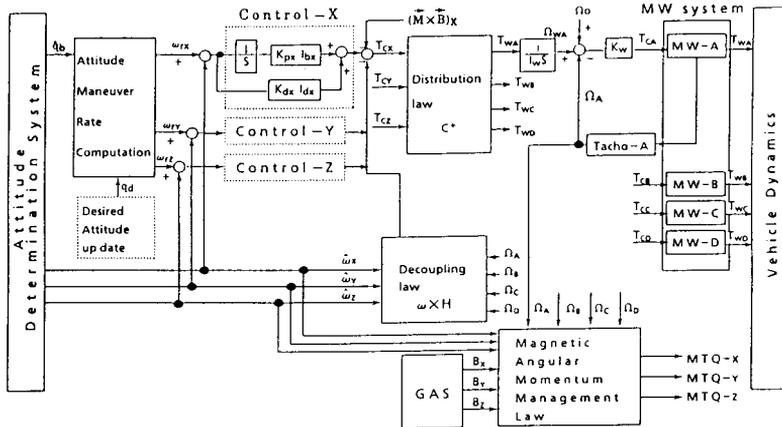


Fig. 4 Mission phase Attitude Control System

The attitude maneuver scheme is such that the satellite body is simply rotated around the instantaneous Euler's rotational axis by an appropriate angle to move from the current attitude to the target attitude. The Euler's rotation axis is uniquely determined and updated on-board for every current attitude given the target attitude, while the reference maneuver rate around the Euler's axis is set constant at 0.2 degs./sec. These are computed at the maneuver control system and output to the pointing control system. As there exists gyro coupling effect between X and Z-axis, which arises from the presence of the bias momentum, the control around each axis is linearized through the decoupling law, this assuring the stable and accurate maneuvers. Fig. 5 shows the maneuverable angular area of the satellite Z-axis in a Hammel diagram with the bias momentum direction taken at the pole.

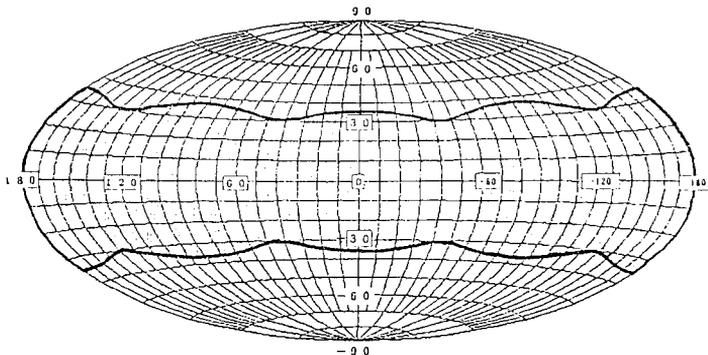


Fig. 5 Maneuverable Range

To maintain a wide attitude maneuverability and to prepare for any ACS contingencies, the direction of the bias momentum is always kept pointing to the Sun, and its magnitude is also kept at nominal value (7.5Nms) by the wheel unloading. The momentum management system is responsible for this wheel unloading, which drives the magnetic torquers in a bang-bang manner with an adequate duty ratio.

### Momentum Transfer Control

After adjusting the satellite spin-rate to 0.9 rpm, this momentum is transferred from the satellite body to the four wheel system by running up the wheel rotors. The simplest and yet elegant method to reorient the angular momentum in the body fixed coordinates is the dual-spin-turn scheme. If the satellite has a suitable mass-property ( $I_z > I_y > I_x$  or  $I_z > I_x > I_y$ ), only the wheel run-up is sufficient to transfer the momentum from the satellite Z to Y axis. Unfortunately, in the ASCA mass-property case ( $I_y > I_x > I_z$ ), this scheme cannot be adopted because such a scheme would cause a nutation of the satellite large enough to incur "attitude upside down". Then, a new control law for the momentum transfer control of ASCA was designed, which relies on the body rate measurement by gyroscopes and wheel-speed measurement by wheel tachometers. The controller is realized by a simple analog circuits. The detail of this control scheme is reported in reference [2].

### Safe-Hold Control

Important points in designing the safe-hold control are to detect an anomaly in the ACS and to assure the safe attitude without ground supports. The items listed below are checked by the hardware or by the on-board software every 125 msec.

- (1) Watch dog timer overflow (\*)
- (2) 2 bits error detection by Hamming code in 64 Kbytes ACP memory (\*)
- (3) Wheel rotor speed anomaly (\*\*)
- (4) Sun angle consistency between the estimated and observed (\*\*)
- (5) Sun angle (\*\*)
- (6) Angular momentum unloading error (\*\*)
- (7) Angular momentum change rate (\*\*)

(\*): Checked by the hardware,

(\*\*): Checked by the software

For the safe-hold control, a simple hard-wired logic is adopted. A running-down of all four wheels and resulting pure spin of satellite is simplest for safe-hold dynamics, but in the ASCA satellite mass property case, it leads to the tumbling of the satellite attitude. Therefore, a concept of "hybrid bias-spin stabilization" scheme is introduced

for the safe-hold dynamics, in which only a pair of wheels out of four runs at the nominal speed and the satellite body spins very slowly. In other words, the body and wheel system share the total angular momentum equally. Of course these activated two wheels are selected according to the result of consistency verification between speed command on wheel tachometer loop and rotor speed. The dynamics of this scheme assures a high stability against the nutation during the transition to and from the safe-hold attitude. This control was also utilized at the initial sun acquisition period by the command from the ground.

## GROUND SUPPORT SYSTEM

Two domestic ground stations, Kagoshima Space Center (KSC) and Sagami Space Operations Center (SSOC), are used for the ASCA satellite operation (see Fig. 6). Through the satellite orbit injection to the establishment of the three axis attitude, the satellite operation was basically conducted at KSC. After the critical phase passed over, the operation center was switched to SSOC.

The support software for the ground attitude control operations are roughly classified into three groups: attitude determination, attitude control operation support, and graphical display of the satellite attitude data. The block-diagram of these software system is also shown in Fig. 6. In the following, the outline of their functions are described briefly.

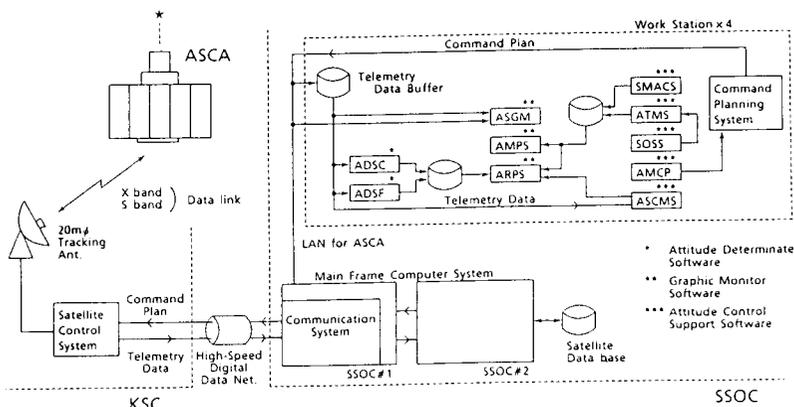


Fig. 6 Ground Operating System for ASCA Attitude Control (Usual Observational Phase)

## Attitude Determination Software

To satisfy the requirements at the initial spin and mission phase, the following two kinds of attitude determination software are prepared.

(1) Attitude Determination Software for Coarse mode (ADSC)

ADSC is used both at the spin phase and at the three-axis stabilized phase. At the latter phase the coarse attitude obtained by the ADSC is used as an a priori attitude for the fine attitude determination to follow.

(2) Attitude Determination Software for Fine mode (ADSF)

This software determines the satellite attitude precisely nominally by using the star tracker and gyro data.

### Attitude Control Support Software

The support software consists of five sub-software, the functions of which are described below. "SMACS" software is for open loop magnetic control and the others are the tools used for the mission phase operation.

(1) Spin-phase Magnetic Attitude Control Simulator (SMACS)

This software generates the command sequence for the magnetic open loop control.

(2) Attitude Maneuver Simulator (ATMS)

This software is used for the command planning such as the evaluation of the time consumption for the attitude maneuver, and the confirmation of the maneuver operation safety.

(3) Stt Operation Support Software (SOSS)

For the planned celestial X-ray object, there remains choices for the target attitude around the telescope axis (satellite Z axis). In selecting the target attitude, at least one appropriate star is needed for the FOV of each star tracker. The SOSS is used to plan the optimum target attitude, reference stars, and their corresponding sub-star catalog.

(4) Acs Macro Command Processor (AMCP)

In the ground operation of ASCA, MACRO command operation system is adopted, which enables the satellite operators to deal with physical values instead of direct binary commands.

(5) Acs Self Condition Monitoring Software (ASCMS)

This software is utilized for two purposes. One is the inspection of the satellite dynamics in the safe-hold mode through the sun angle and gyros data. The another purpose is to sample the telemetry data from the ACS components during the mission phase once a day, and then check the ACS health. The sampled data are stored as the ACS time-log.

Initial Attitude Acquisition

The initial attitude acquisition sequence of the satellite is shown in Fig. 7. By the third stage of the M-3S II launch vehicle, the satellite was injected into an orbit with 132 rpm spin around the satellite Z axis. Ten seconds after the rocket separation, the yo-yo despinner was deployed and the spin-rate was reduced to 8.1 rpm. After that, the satellite was kept in a spinning state days to adjust its spin-rate and to precess its spin-axis in an inertial coordinate frame.

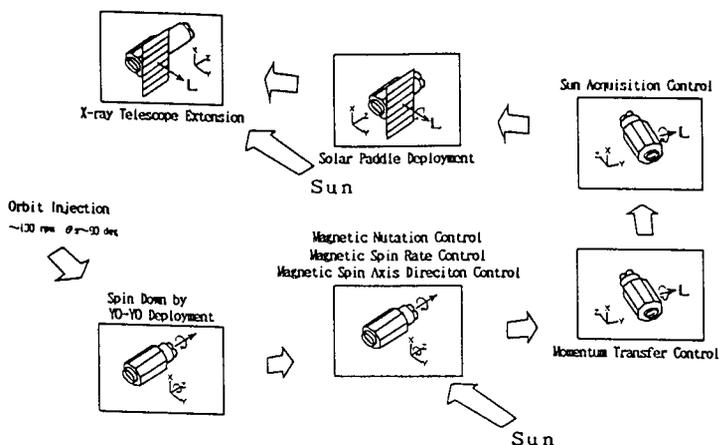


Fig. 7 Initial Attitude Acquisition Sequence

Through Feb. 20th to 23th, this spin-rate (or equivalently angular momentum) is reduced from 8.1 rpm to 2.8 rpm, and then to 0.86 rpm. The spin-direction control from Feb. 20th to 23th is requested to assure a favorable spin-axis attitude for the communication link with the ground station (KSC). Through this period as the satellite configuration is spin-astable, the nutation is actively suppressed by the magnetic nutation control. After the angular momentum adjustments the momentum transfer control was initiated on Feb. 24th. This momentum transfer law newly adopted for the ASCA was successfully performed as is seen in Fig. 8, in which body angular rates sensed by the gyros during the maneuver are shown. After the completion of the momentum-transfer control, the sun acquisition maneuver was started. The Solar paddle was successfully deployed in the safe hold control mode, then moved to mission phase attitude control mode. The EOB was extended quietly under the attitude control of pointing mode. The history of the initial attitude acquisition is shown in Table 1.

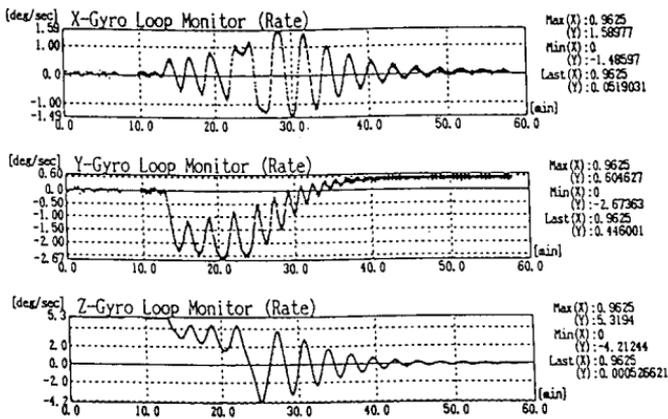


Fig. 8 Body Angular Rates During The Momentum Transfer Control

Table 1  
ASCA INITIAL ATTITUDE ACQUISITION SEQUENCE OF EVENTS

date	Events
1993/ 2/20 02:08	Orbit injection
	Spin axis direction right ascension $\alpha = 41.1\text{deg}$ declination $\delta = -4.6\text{deg}$
1993/ 2/20 02:09	yo-yo deployment from 129.6rpm to 8.1rpm
1993/ 2/20 03:45	Magnetic nutation control
1993/ 2/20 22:41	First magnetic spin-rate control
~ 2/21 13:45	from 8.1rpm to 2.8rpm
1993/ 2/21 21:07	First magnetic spin axis direction control
~ 2/22 15:08	final spin axis $\alpha = 24.5\text{deg}$ $\delta = -56.2\text{deg}$
1993/ 2/22 23:21	Second magnetic spin axis direction control
~ 2/23 21:00	final spin axis $\alpha = -93\text{deg}$ $\delta = 2\text{deg}$
1993/ 2/23 21:05	Second magnetic spin-rate control
~ 2/23 23:56	2.8rpm $\rightarrow$ 0.86rpm
1993/ 2/24 22:42	Momentum transfer control by momentum wheels run-up
1993/ 2/25 00:23	Sun acquisition maneuver Y axis//solar vector
1993/ 2/25 02:05	Solar paddles deployment
1993/ 2/27 21:05	Fine pointing control mode start
1993/ 3/01 19:21	Extendible Optical Bench extension (ASCA acquired its final in-orbit configuration)

## Mission phase Attitude Control

The attitude control performance at the mission phase can be evaluated at the following four stand points of view.

- (1) On-board attitude Determination
- (2) Pointing accuracy and stability
- (3) Attitude maneuverability
- (4) Performance of angular momentum management

### On-board attitude Determination

After the steady state attitude acquisition, the star trackers are operated for their initial in-orbit functional check. The functions and performances of the on-board attitude determination system(ADS) are evaluated in parallel. The main functions of the ADS on-board are to eliminate the attitude determination errors and the gyro rate bias estimation error. The evaluated ADS performance is summarized in Table 2. Because of the thermal distortion problem, the accuracy of the ground attitude determination could not satisfy the requirement (see next section).

### Pointing Accuracy and Stability

As the absolute pointing accuracy is described in the preceding section along with ADS performance, only the short term stability are discussed here. The typical attitude fluctuation in the pointing mode is shown in Fig.9. The pointing stability is quite high as 0.0001 deg/sec during the period the magnetic torquers are not excited. While, when the magnetic attitude control is acting, this magnetic control affects the satellite attitude and deteriorates its stability. The instance of the attitude stability during the magnetic torquer exiting is shown in Fig.10. Although this stability under the magnetic control is well within the required level, there remains a possibility to improve this further as described below. The stability deterioration by the magnetic torquer comes from its driving scheme. For the benefits of hardware simpleness, the ASCA magnetic driving electronics adopted a bang-bang method, in which a step shaped torque profile is supplied by the magnetic torquers. In the design phase, it is expected that the counter wheel torque by the feed-forward loop of the ACP software, cancels out the magnetic torque.

Unfortunately, this attempt does not work well due to the lag-time in the wheel tachometer loop. The orbit data shows the interference level is reduced to the one-third of the without feed forward loop case. According to the analysis, by tuning the magnetic torque timing correctly, further reduction of the interference up to one-tenth is expected.

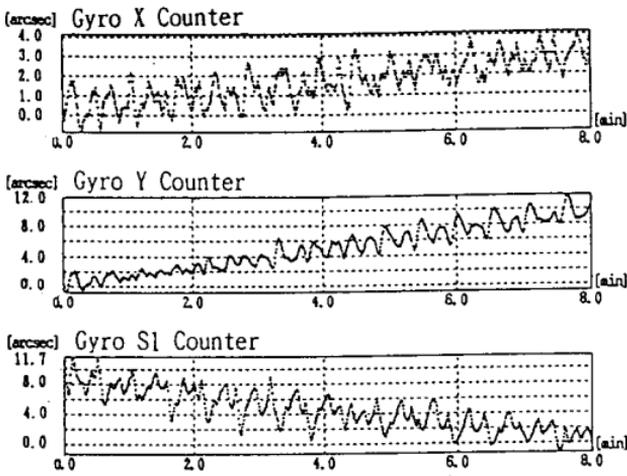


Fig 9 Attitude Stability without Magnetic Torquer Driving

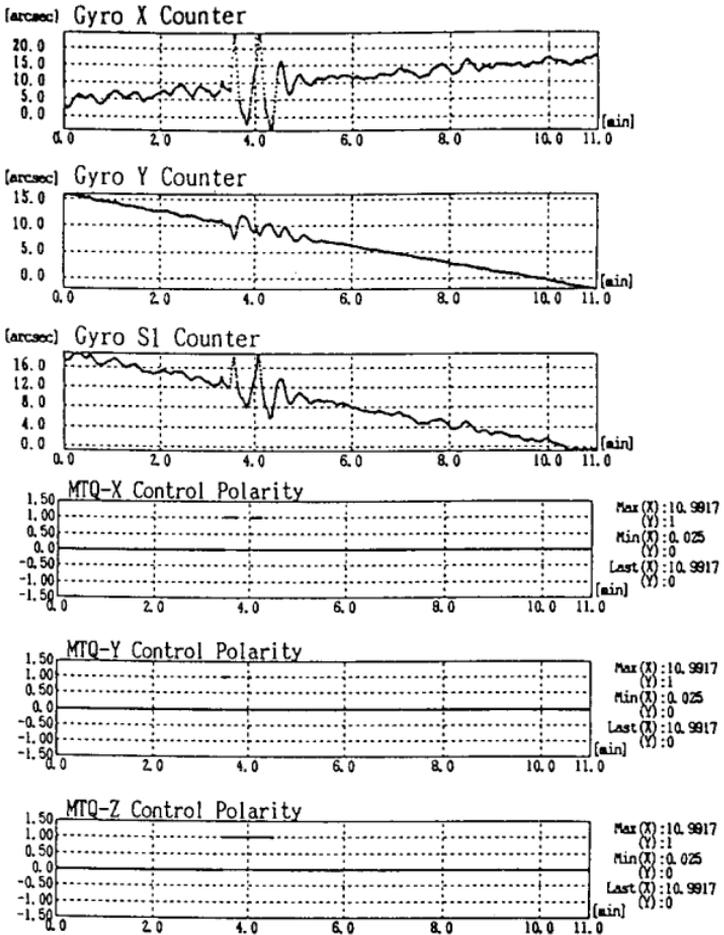


Fig 10 Attitude Stability with Magnetic Torquer Driving

## Attitude Maneuverability

As it was the first experience for the ISAS scientific satellites to implement the ACS with such a high and large maneuverability, one of the most concerns to us is that the ACS is able to manage a large angle maneuver successfully as designed, especially, it is able to re-lock on the new target stars without the ground supports after the maneuver.

Despite of our suspense, the maneuvering system works quite well. An example of the satellite attitude profile during the maneuver is shown in Fig.11. Through this one year operation, there was no maneuver trouble except for the case, in which a gyro contingency caused the abnormal maneuver and system fell into the safe-hold mode, which will be described in the following section as "Gyro Anomaly".

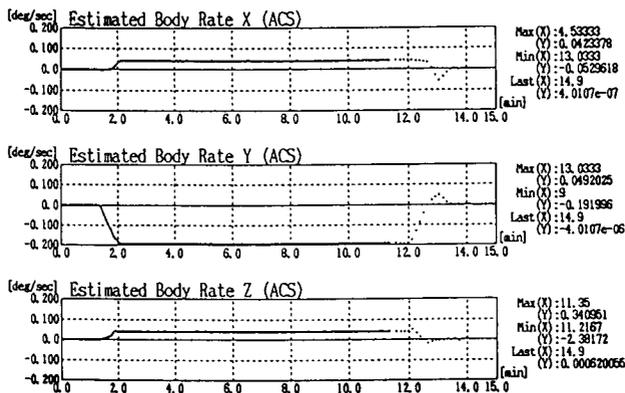


Fig.11 Body Rate Profile During Attitude Maneuver

## Angular Momentum Management

In the mission phase, the satellite total angular momentum is magnetically controlled to point to the Sun and its norm to the nominal value of  $7.5 \pm 1.5$  Nms. According to the flight data, the direction and norm error of the momentum is less than 8 degs. and 1.1 Nms respectively. These results are close to the values obtained by simulation.

Table 2  
THE ASCA MISSION PHASE CONTROL PERFORMANCE

Pointing Control:		Verified	Required	
(1)Absolute	Z axis direction;	0.015	0.017	deg ( $3\sigma$ )
	around Z axis;	0.015	0.17	deg ( $3\sigma$ )
(2)Stability	Z axis direction;	0.0015	0.0033	deg/32sec ( $3\sigma$ )
	around Z axis;	0.0056	N. A.	deg/32sec ( $3\sigma$ )
Maneuver Control:				
(1)Speed	Maximum Speed;	0.2	~0.2	deg/sec
(2)Acquisition Accuracy		0.3	N. A.	deg
Angular Momentum Management:				
(1)Amount Control		1.0	N. A.	Nms ( $3\sigma$ )
(2)Direction Control		8.0	N. A.	deg ( $3\sigma$ )
On-board Attitude Determination:				
(1)Attitude Determination Accuracy				
	before STT calibration;	0.3	N. A.	deg ( $3\sigma$ )
	after STT calibration;	0.015	N. A.	deg ( $3\sigma$ )
(2)Gyro Rate Bias Estimation Accuracy		0.002	N. A.	deg/Hour ( $3\sigma$ )
Ground Attitude Determination:				
(1)Attitude Determination Accuracy				
	before STT calibration;	0.3	N. A.	deg ( $3\sigma$ )
	after STT calibration;	0.015*	0.005	deg ( $3\sigma$ )
(2)Gyro Rate Bias Estimation Accuracy		0.002	N. A.	deg ( $3\sigma$ )

\* refer to the following section.

## ASCA EXPERIENCES

### Robustness of On-Board Attitude Determination System

In the early stage of the functional check of the mission phase control, the ADS could not work stably as designed due to the following reasons. In the design phase, the star tracker was modeled to have Gaussian random noise, and was not expected to generate accidental large errors in their tracking data which are caused by cosmic ray events, stray light from the bright earth edge, and, etc. In the initial design, the ADS parameters were tuned to converge rapidly in the gyro rate bias estimation process, considering of the possibility of the large rate bias shift after the launch. However, this rapid conversion nature of the filter design brought the rather worse performance due to the presence of the accidental large errors. Once accidental noise happen in this system, the attitude control system (including on-board ADS) falls into a limit cycle

motion as follows.

- (1) If the ADS gets wrong star tracking data from the star trackers, it makes large compensation on the gyro rate bias. In the initial ADS system, the weight coefficient for the STT data was selected large compared with that of the gyro data. Due to this, if STT tracking data have large error, the ADS updates the gyro rate bias incorrectly.
- (2) The gyro rate bias is actually quite stable (less than 0.001 deg/H).
- (3) Then, the estimated attitude based on the incorrectly updated gyro rate bias begins to drift.
- (4) If there is sufficient time before the star tracker occultation, ADS has a chance to recover. If it not so, the satellite attitude drifts during the STT occultation. In this case, at the resume of the star tracking, the ADS detects the larger attitude error and then makes larger compensation on the gyro rate bias. At this time the gyro rate bias error grows up so large to converge during the short STT available period.
- (5) The accidental large errors of the star tracker data mentioned above were usually generated at the beginning or end of the STT occultation. Then, the ADS system easily falls into this limit cycle motion.

The typical limit cycle motion is shown in Fig.12, in which the maximum attitude error at the end of the STT occultation grew more than 0.006 deg. To resolve this problem, two kinds of approach were taken. One is to eliminate the transient errors in the tracking data at the STT side. The other countermeasure is to tune the Kalman-filter in the ADS by adopting the more gyro-weighted parameters. Both of these two improvements were employed by revising the on-board software of the STT and ACP. The results after this tuning are shown in Fig.13. As is seen from this figure, there was a considerable improvement in the ADS stability against the accidental STT errors.

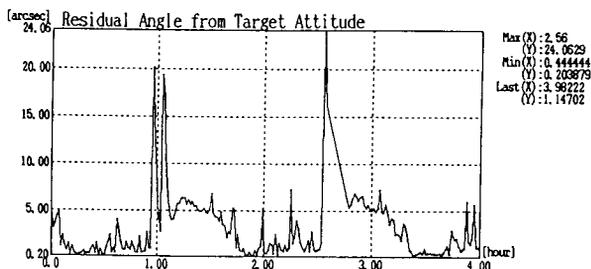


Fig.12 Flight Results of On-board ADS Before Tuning

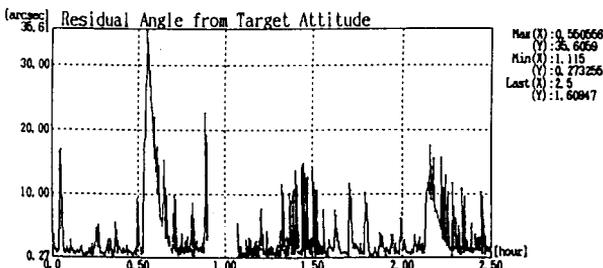


Fig 13 Flight Results of On-board ADS After Tuning

Pointing anomaly due to thermal distortion of the satellite structure

After the initial attitude acquisition and brief functional check in flight, the ASCA entered into the mission phase. In the little while, it was found that there is a mismatch of 0.015 degs. between the attitudes propagated by the IRU data and that observed by the STT's, and that the controlled attitude was also influenced by the same order. The STT star tracking data during several orbits is shown in Fig.14, in which the attitude control was performed by only IRU based ADS, in other words, with no STT calibration. It is easily known that there is orbital periodic fluctuation especially in the STT H direction, or around the satellite the X axis. Also, it can be seen that, this fluctuation has a obvious correlation with a satellite day-night condition (see sun presence flag of sun sensor data). After the detailed analyses of the fight data, it was concluded that there is some thermal distortion in the satellite structure, and small relative rotation between the IRU mounted base plate and the STT mounted plate caused the data mismatch between the IRU and STT.

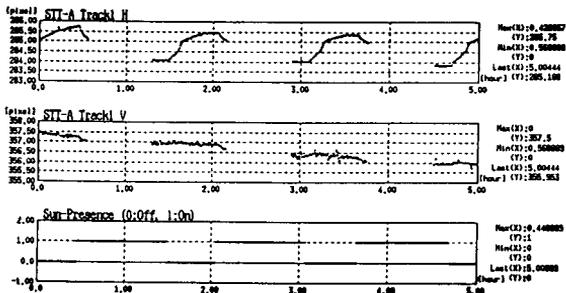


Fig.14 STT Star Position History with ADS STT Cal Disable Mode

It is now being tried to compensate this thermal distortion which varies with the day-night condition and the Sun direction in the satellite body frame at the ground data processing. In this compensation the rotation amplitude profile of the IRU base plate relative to the STT based coordinate system is evaluated and formulated by fitting the large amount of the flight data.

### Unexpected Transition To The Safe-Hold Attitude

The on-board attitude control software of the ASCA has several kinds of safety check functions. By introducing these functions, it becomes possible to detect ACS abnormalities or malfunctions without ACS experts and to reliably transfer to the safe hold mode in case of the ACS contingency. In the initial period of the mission phase, this on-board safe check system detected abnormalities in the ACS once a week and every instance of the abnormality detections, it went into the safe hold mode. At that time the satellite operation schedule was confused and the cause of these transitions was not clarified because of poorly reported telemetry data. Especially, once happened the abnormality in the ACS, several other abnormalities are sequentially induced by the initial anomaly as a seed, and the ACS data which are important for the analysis of these phenomena, were over-written by the new data within a quite short time compared with the telemetry sampling time interval. Unfortunately, in the initial safe check system, most of the check item were evaluated every 125 msec and if only one of their values is over the specification, the system immediately moves into the safe hold mode. To solve this problem, the on-board attitude control software was changed at the two parts; One is the revision to latch the originally detected abnormality in the telemetry and the other one is the switching logic improvement, in which the transference to the safe hold mode is allowed only after the three successive abnormality detections. The conclusion obtained through the flight data analyses is that there is a kind of thermal stress-energy relaxation phenomenon in the ASCA structure. Gyro integration counter data which were obtained after the software revision is shown in Fig.15. From these data, it can be seen that all the gyros sense small impulsive fluctuations simultaneously, and the counter values are up and down in a short time interval then returned to their original level. If this phenomenon is due to the IRU component itself, it becomes difficult to explain why the outputs return to the original levels because each gyro data is integrated at the another equipment, i.e. ACP. Further, after the S1 gyro switched to S2, the same phenomena was observed in the S2 gyro output nevertheless S2 is independent component from S1 gyro. These impulsive fluctuations usually happen at nearly the same orbital position of 5 minutes before the satellite sun-rise. It is natural to consider that at this timing the thermal condition of the satellite structure is reached to release the thermal stress energy.

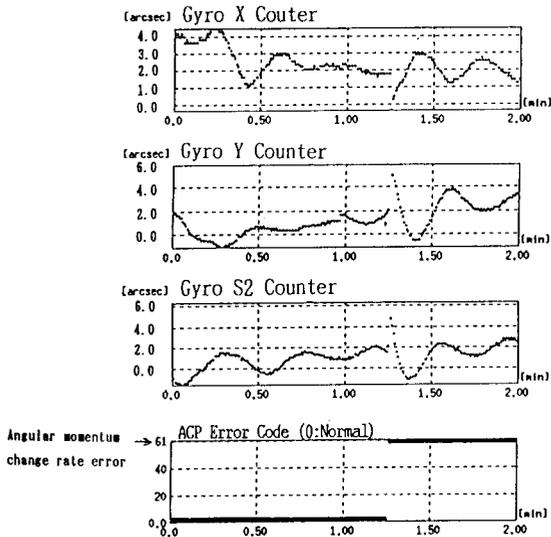


Fig.15 Gyro Integration Counter (After Software Touch up)

### Anomalies During Attitude Maneuver Due To Gyro Degradation

At the initial mission phase, the X, Y, and S1 gyros are selected as the operational inertial sensors for the attitude determination and Z gyro as standby sensor for the ACS contingency. Last Sep. 7th, ASCA was fallen into the safe hold mode during the course of large angle maneuver. Before this maneuver, the pointing control system seemed working well. However, during the maneuver, something happened in the mission phase control system. According to the telemetry data it was found that, after the maneuver start the sun direction which the on-board ADS expected based on the IRU data, began to separate from that the TDSS observed. The sun angle discrepancy more than 15 degrees was detected by the on-board software, and finally the ACS fell into the safe hold mode. The angle between the satellite Y axis and the sun direction which is calculated using the gyro output is shown in Fig.16. In this figure, there is no variation in the sun angle, in other words, the ACS believed that it was performing a normal maneuver until the detection of the abnormal sun angle by the TDSS. As is seen in Fig.17, the sun angle by the TDSS is quite different from the above. To examine the cause of this 'sun angle discrepancy', the satellite dynamics was simulated by using the history of the telemetered wheel rotation speed during the maneuver. By differentiating the wheel speeds, the reaction torque acting on the satellite body was obtained. Then, by integrating the wheel reaction torque plus theoretically calculated gravity gradient torque which is dominant external torque source, the satellite dynamic motion was estimated without the gyro data. In this way, the integrated gyro counter outputs are also estimated, and the abnormal gyro among three gyros was identified by comparing the telemetry counter values and the above estimated one. Only the S1 gyro counter has a difference more than 2.5 deg. from the simulated dynamic motion. The later analysis further showed the scale factor shift of about 10 % for this gyro.

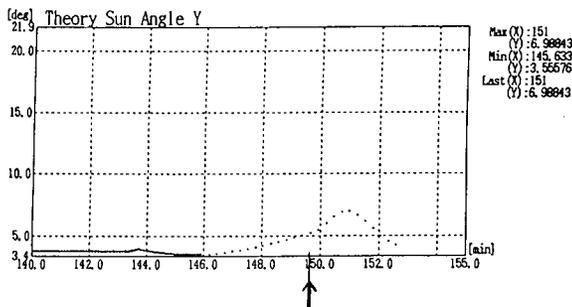


Fig. 16 Estimated Sun Angle Y from IRU Outputs

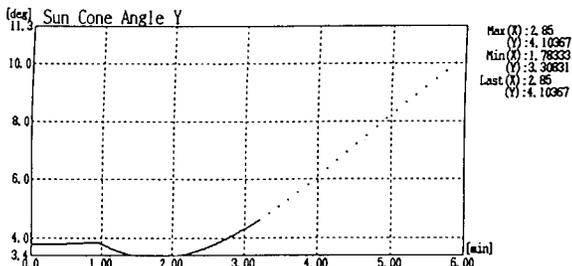


Fig. 17 Observed Sun Angle Y by Sun Sensor Outputs

#### CONCLUDING REMARKS

The attitude control system of ASCA adopts unique and newly developed schemes such as the momentum transfer control during the initial attitude acquisition and the hybrid bias-spin attitude stabilization for the safe-hold attitude control. The momentum transfer control worked well as expected. The sufficient stability and usefulness of the hybrid bias-spin stabilization dynamics was verified in orbit. The attitude pointing control in the mission phase, achieved satisfactory accuracy and stability. On the other hand, valuable experiences were obtained through the in-orbit operations of the attitude control system, which are to be reflected to the attitude control of the feature astronomy missions of ISAS.

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