THE FLIGHT RESULTS OF THE NEWLY ONBOARD ATTITUDE DETERMINATION OF ADEOS-II

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ABSTRACT

ADEOS-II (MIDORI-II) is the large Earth observation satellite. The new method of the attitude determination system we called “Hybrid navigation mode” was loaded with GPSR freshly on ADEOS-II. The Hybrid navigation mode has improved the accuracy because the pitch attitude is determined by Fine Sun Sensor (FSSA), which can be realized by the GPSR. In addition, the seasonal correction law of the Earth radiance error of Earth Sensor (ESA) was used freshly, and this correction improves the roll attitude.

The ground evaluation and validation of the attitude ware executed using the telemetry data of attitude and orbit control subsystem (AOCS) sensors and the star sensor which is loaded independently of AOCS as experimental device, and it is verified that the satisfactory attitude have been maintained during ten months.

1. INTRODUCTION

ADEOS-II (ADvanced Earth Observation Satellite II, MIDORI-II) is the large Earth observation satellite of the sun synchronous low Earth polar orbit. The size is 6m by 4m by 4m and the weight is 3.7ton. It has the large flexible solar array paddle that size is 3m by 24m. It has 5 Earth observation sensors. The control method of the attitude and orbit control subsystem (AOCS) is 3-axes zero momentum control system. The specification of the attitude control accuracy is 0.3deg at each axis (3sigma), and the attitude knowledge accuracy is 0.10deg, 0.08 deg, and 0.14deg at roll, pitch and yaw axis respectively (3sigma).

Even though the AOCS of ADEOS-II follows in the ADEOS’s footsteps, the GPSR and the new method of the attitude determination system we called “Hybrid navigation mode” were loaded freshly. GPSR was loaded because the payload required the high accurate information of the satellite time and position. The hybrid navigation mode was developed as an effective utilization of the GPSR for the improvement of the attitude determination accuracy.

For the ground attitude evaluation and validation, one head of the star sensor was loaded independently of AOCS as experimental device on the way of the development of satellite flight model. This star sensor is not in the loop of the AOCS and only downloads the independent attitude information to the ground station.

ADEOS-II was launched in December 2002 and finished the operation in October 2003 because of the accident of the loss of the power. The ground evaluation and validation of the ADEOS-II’s attitude was executed using the telemetry data of AOCS sensors, payload observation sensors, and the star sensor. Although the life was short, it was verified that the satisfactory attitude has been maintained and the conditions of the Satellite attitude, dynamics, and the attitude and orbit control subsystem (AOCS) components were kept stable during ten months.

This paper introduces the new method of the attitude determination system and the flight results of the AOCS, i.e. the results of the ground attitude evaluation, calibration and validation.

2. ATTITDE DETERMINATION SYSTEM

The newly onboard attitude determination system “Hybrid Navigation mode” was loaded with ADEOS-II. As ADEOS-II is a successor of ADEOS, the attitude determination system of ADEOS was also loaded for the backup system we called “Conventional navigation mode”. The conventional navigation mode is used in the initial operation, and it is moved to the hybrid navigation mode after the GPSR starts operation. If something is happen to GPSR, the attitude determination mode is switched to conventional navigation mode automatically.

2.1 Conventional Navigation Mode

The Conventional navigation mode is based on the roll-yaw gyro compass attitude determination system with Earth Sensor (ESA) and 3-axes Inertial Reference Unit (IRU). The roll/yaw attitudes and the yaw gyro drift are estimated by ESA roll and IRU roll/yaw rates. The roll gyro drift is determined by yaw axis Fine Sun Sensor (FSSA). For the pitch axis, the pitch attitude and the pitch gyro drift is estimated by ESA pitch and IRU pitch rate. The block diagram of the conventional navigation mode is shown in Fig.1.

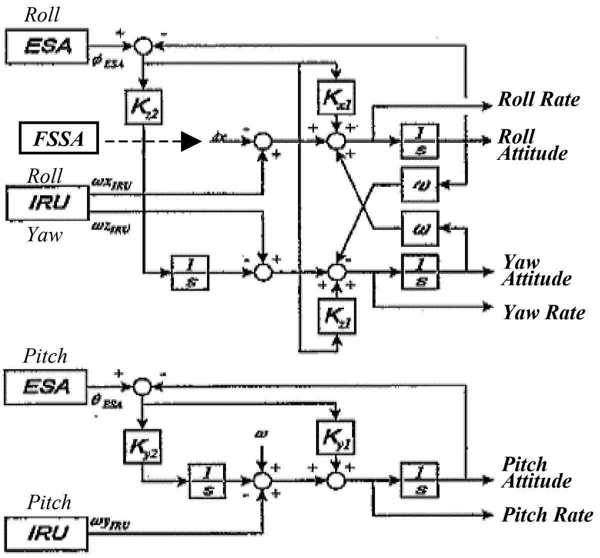

Fig.1 Block diagram of Conventional navigation mode

The attitude determination accuracy of this system is mainly subjected to the accuracy of ESA. Although the random noise of the ESA can be reduced by the kalman filter, the Earth radiance error affects the attitude determination accuracy. The Earth radiance error is the dominant primary error factor of ESA, and this is caused by the temperature fluctuation of local weather or seasonal change. The Earth radiance error is not the random error but the bias error, but this bias is changed in low frequency. Then it is difficult to reduce this error by the attitude determination filter.

Another error source of this system is the accuracy of the satellite position in the orbit, because the accuracy of the satellite attitude information derived from FSSA depends on it. The satellite position is calculated from the satellite time and the orbit ephemeris determined by the ground station. Because it is difficult to keep the satellite time accurate, the accuracy of the roll gyro drift estimation by FSSA is restricted, and this causes the yaw attitude error.

2.2 Hybrid Navigation Mode

The hybrid navigation mode uses not only the yaw axis of FSSA but also the pitch axis of FSSA instead of the pitch axis of ESA, which can be realized by the high accurate real-time information of the time and the satellite position in the orbit from the GPSR. The block diagram of the hybrid navigation mode attitude determination system is shown in Fig.2 and Fig.3.

The differences of the roll/yaw determination system between conventional navigation and hybrid navigation are the algorism of the roll gyro drift estimation and the orbit regression rate compensation. Owing to the high accurate information of satellite position and time, the yaw attitude information derived from FSSA yaw can be improved and it is possible to estimate the roll gyro drift accurately by the kalman filter. This improves the yaw attitude. Owing to the orbit regression rate compensation, it is possible to decrease the kalman filter gain of ESA. This can reduce the influence of the Earth radiance error, so that the roll attitude is improved. As the roll attitude error couples to the yaw attitude error, the yaw attitude is also improved together.

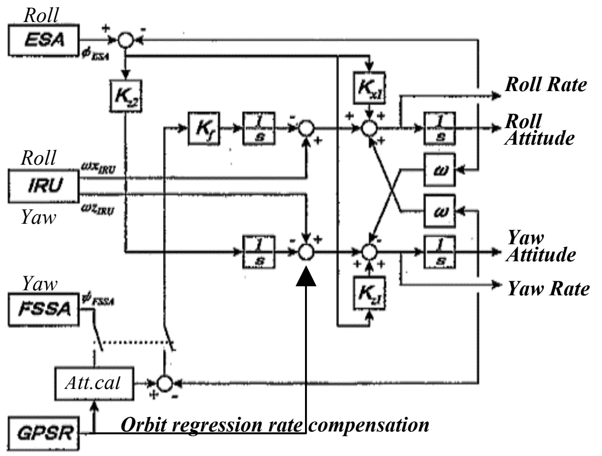

Fig.2. Hybrid navigation mode (Roll/Yaw)

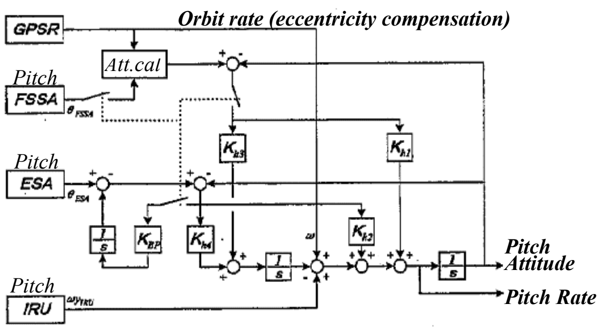

Fig.3. Hybrid navigation mode (Pitch)

The pitch attitude of the hybrid navigation mode is determined not by ESA but by FSSA mainly. Therefore the pitch attitude is not affected by ESA's error, so that the attitude accuracy is improved. During the orbit position where FSSA can be used, the FSSA is used for the updating of the pitch attitude, gyro drift and bias error between ESA and FSSA by the rather big gain. As the satellite rotates at -0.06deg/sec around the pitch axis, the time error yields a large error of pitch attitude when the pitch attitude is determined by FSSA. Owing to the GPSR, a very accurate pitch attitude can be derived from FSSA. During the period when FSSA cannot be used, ESA is used with small gain. It becomes possible to make the gain of ESA small substantially, that the eccentricity compensation is done by GPSR data.

2.3 ESA Seasonal Correction Law

The seasonal correction law of the Earth radiance error of ESA was offered from the ESA production manufacturer (SODERN), and this was used freshly in ADEOS-II. This correction law is for the latitude by season. The equation of the correction law is the Fourier series function of latitude, and Fourier coefficients are supplied every week. As it is thought that the Earth radiance error depends on not only latitude but also longitude, and also depends on the local weather, the effect of this correction law was questioned before launch. But this correction was rather effective, as we'll mention in section 4. The attitude determination error of the roll axis was decreased, and also the yaw axis which is coupled with roll attitude was improved.

3. GROUND ATTITDE EVALUATION

The continual telemetry data of all orbits becomes available in ADEOS-II and the evaluation of the satellite attitude, dynamics and the health of the sensors and actuators have executed by the abundant flight data among the satellite operations. The ground attitude evaluation and validation was executed using the telemetry data of AOCS sensors, payload observation sensors, and the experimental star sensor.

3.1 Consistency and Misalignment Estimation

At the first step of the ground attitude evaluation, we checked the consistency between the attitude sensors (ESA, FSSH, IRU, STT) each other. The example of the consistency check result is shown in Fig.4.

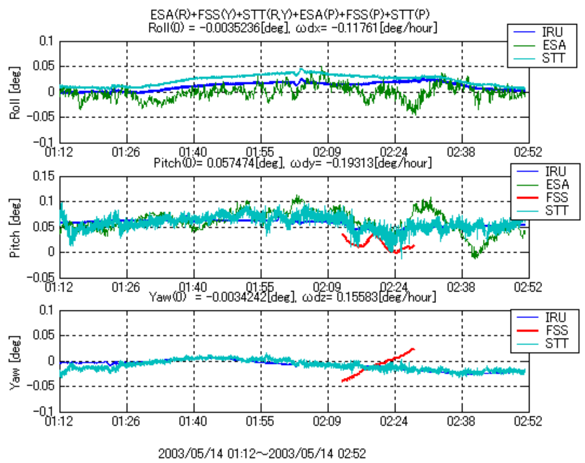

Fig.4. Sensors consistency check results (before alignment shift compensation)

IRU attitude means the gyro integrated attitude. The attitude information of each sensor is converted to Euler angle using only ground measured misalignment compensations. The attitude is rather consistent with each other than expected. But there are some discrepancies within about 0.05deg. These discrepancies indicate the occurrence of some alignment shifts in the orbit.

The misalignments between each sensor are estimated as shown in Table.1. As we can only estimate the relative misalignment, then we choose the reference sensor for each axis. The reference of roll and pitch axes are ESA and the reference of yaw axis is FSSA. The independent verification of attitude was carried out by the third party (US company). The estimation results of alignment shifts between us and the third party are agreed well as shown in Table.1.

Table 1. Misalignment estimation Results (alignment shift from ground measurement) [deg]

	JAXA / NTSpace	Third Party
ESA Roll	Reference	
ESA Pitch	Reference	
FSSY Roll(*)	0.0604	0.0593
FSSP Pitch	-0.0460	-0.0457
FSSY Yaw	Reference	
STT Roll	0.0210	0.0180
STT Pitch	-0.0014	-0.0009
STT Yaw	-0.0054	-0.0022

(*)Around the optical (boresight) axis of FSSA head

These alignment shift estimation results are reflected to the ground attitude evaluation. The result of the sensors consistency check after alignment shift compensation is shown in Fig.5.

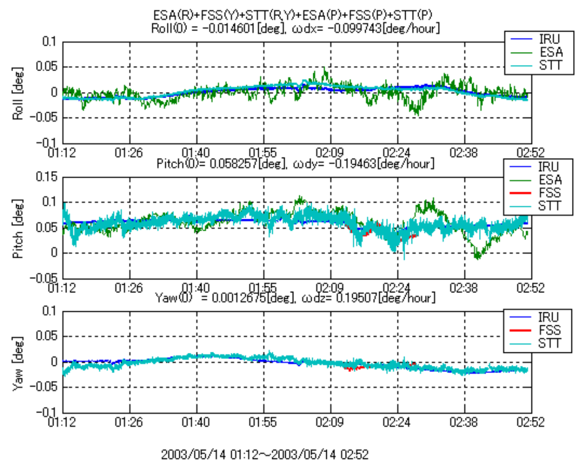

Fig.5. Sensors consistency check results (after alignment shift compensation)

Each sensors attitude is agreed well. Although there are bias errors between FSSA pitch and other sensors pitch and between ESA roll and STT roll, and there is a difference of slope between FSSA yaw and other sensors yaw in Fig.4, these discrepancies are almost eliminated in Fig.5. There remains some error in ESA. This error may be caused by the Earth radiance error. STT pitch attitude is rather noisy, because pitch axis corresponds to the boresight of STT. STT has low sensitivity in this direction. STT roll attitude corresponds to horizontal and vertical (HV) axis of STT, and this axis's accuracy is very well. Pitch attitude has the offset of about 0.05 deg. The cause of this pitch attitude offset is the bias offset between ESA pitch and FSSA pitch. Pitch attitude is determined by the reference of the FSSA coordinate system in the hybrid navigation mode. Then if we choose the ESA coordinate system for the reference of the satellite attitude, pitch attitude always has a bias (about 0.05deg) during the hybrid navigation mode. We'll mention this problem at later section.

Each sensors attitude output is rather consistent and accuracy performance is well compared with each sensor's specification after misalignment compensation. We calculate the optimal estimated attitude using the least square algorism with these sensor's outputs. We have the confidence that this optimal estimated attitude in the ground is fairly reliable.

3.2 Ground Estimated Attitude

We have evaluated the attitude of ADEOS-II during the normal operation phase (i.e. after initial checkout phase) when the continual telemetry data of all orbits is available.

Fig.6 shows the 14 orbits in one day of the optimal estimated attitude. The transverse axis shows the argument of latitude, and it starts from the ascending node to the next ascending node. The attitude of each orbit is over plotting.

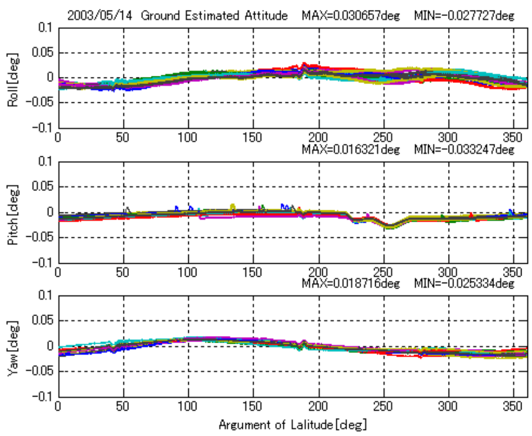

Fig.6. Ground estimated attitude on 14th May 2003

The hybrid navigation mode keeps high accurate attitude, and it is very stable. Roll attitude fluctuates slightly because of the Earth radiance error of ESA. But the influence of this error is rather reduced. Pitch attitude is very stable because ESA is not mainly used. The FSSA coordinate system is chosen for the reference of the pitch attitude, because the FSSA is the main sensor in the hybrid navigation mode. There are some fluctuations near the argument of latitude 250deg. The FSSA updates the attitude around this area, and these fluctuations are caused by the error of the transfer function of FSSA. The field of view (FOV) of FSSA is +/- 32deg and we use within +/- 25deg. The specification of the transfer function error is within +/- 0.02deg and flight results are barely within specification. When FSSA is used for the yaw attitude determination in the conventional navigation mode, the Sun doesn't move widely in the FOV of FSSA so much. When FSSA is used for the pitch attitude, the Sun moves overall of the FOV of FSSA. Then the transfer function error is significant for the FSSA pitch. Yaw attitude is determined accurately by FSSA yaw, and yaw attitude fluctuate slightly because of the roll/yaw coupling.

Fig.7 shows the worst attitude data among the ground evaluations. The Earth radiance error of ESA roll becomes large and this error couples with yaw attitude error. It is known that the Earth radiance error near the pole becomes large in winter. This error corresponds to the winter of the South Pole. The reason of the Pitch error (divided to two groups) is the on-board parameter commands about Sun position and orbit information which was sent on every Tuesday noon. These parameters are interpolated till next Tuesday. The standard deviation of the attitude error during one day became the worst on 19th August 2003.

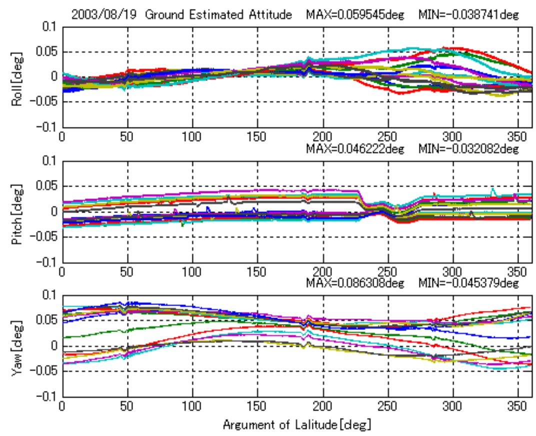

Fig.7. Ground estimated attitude on 19th August 2003

Fig.8 shows the attitude near the autumn equinox. The roll error caused by the Earth radiance error of the South Pole is vanished. The yaw attitude has an offset error, which is caused by the precision of the interpolation of the Sun position in the onboard software.

Fig.9 shows the attitude of the day before the accident. The Earth radiance error near the North Pole becomes large. The attitude had been kept well till the last hours, and there was no sign of anomaly. The accident happened suddenly from the AOCS point of view.

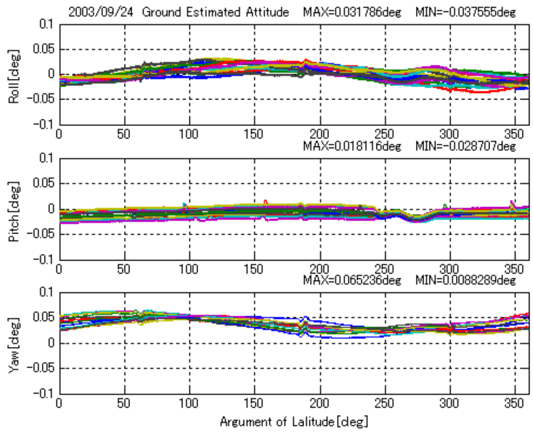

Fig.8. Ground estimated attitude on 24th September 2003

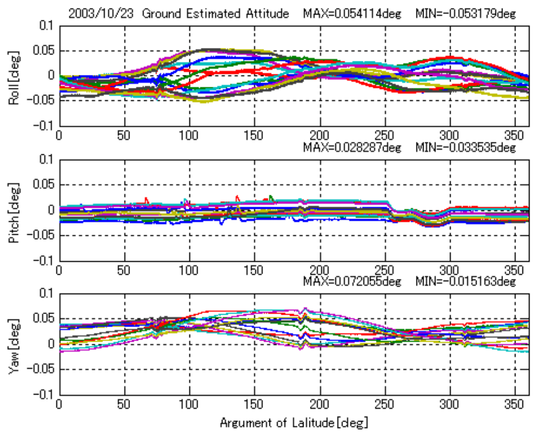

Fig.9. Ground estimated attitude on 23th October 2003

3.3 Onboard Attitude determination Evaluation

Onboard attitude determination data is distributed to the payload sensors directly on the satellite. We have evaluated the onboard determination attitude using the above ground estimated attitude. Fig.10 shows the difference between onboard determination attitude and ground estimated attitude. As we believe that the ground estimated attitude is correct, the difference between ground and onboard corresponds to the attitude determination error of the onboard. The onboard determination attitude detects accurately the high frequency attitude error which we called dynamics error, but it doesn't detect the low frequency attitude error. As we mentioned in section 3.2, the Earth radiance error (low frequency bias change) of ESA, transfer function error of FSSA and the Sun position interpolation precision are the major cause of the attitude determination error of the hybrid navigation mode.

The ground estimated attitude is effective to compensate a low frequency error at a mission payload side (for example, the geometric compensation etc.). But the onboard determination attitude is also enough to compensate a high frequency error (for example, the compensation between lines of detectors etc.).

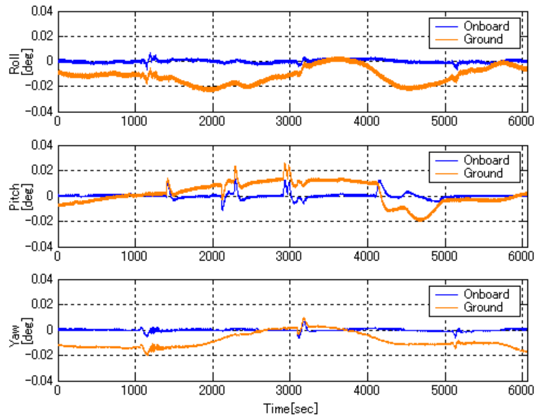

Fig.10. Onboard attitude and ground estimated attitude

3.4 Attitude Evaluation Results

The specification of the attitude accuracy is defined as 3 sigma of the standard deviation. We calculated all of the standard deviation during the hybrid navigation mode. The result is shown in table.2. As shown in Fig.10, the flight results of the dynamics error of ADEOS-II was very small, the attitude determination accuracy is almost the same as the attitude control accuracy. The attitude of ADEOS-II was very well and kept within specification in the hybrid navigation mode.

Table 2. Attitude Evaluation Result of Hybrid Navigation mode [deg] (3sigma)

	Attitude Control Evaluation Result	Specification	
		Determination	Control
Roll	+/- 0.050	+/- 0.10	+/- 0.30
Pitch	+/- 0.042	+/- 0.08	+/- 0.30
Yaw	+/- 0.069	+/- 0.14	+/- 0.30

The maximum and minimum of the attitude error among one day is plotted in Fig.11 to Fig.13 for each axis. The transverse axis shows the date. The satellite was operated in the conventional navigation mode in the blank part of these figures. The maximum or minimum of attitude becomes larger than specification value at 5 times in pitch axis. These errors were caused by the GPSR bad visibility or anomaly. As these errors were resolved within a short time, the standard deviation of the attitude error doesn't become worse so much. There is no data which is larger than specification value in roll and yaw axis. As the yaw attitude sometimes has the bias error caused by the Sun position interpolation precision, the standard deviation becomes larger. We pause to realize how difficult to evaluate the attitude in the long duration while a transition or an anomaly is occurred.

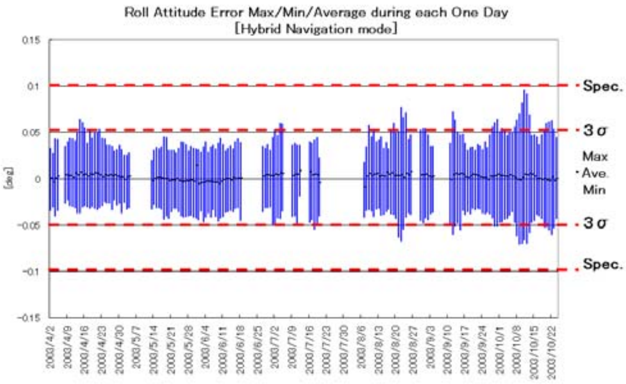

Fig.11. Roll Attitude Error among each day

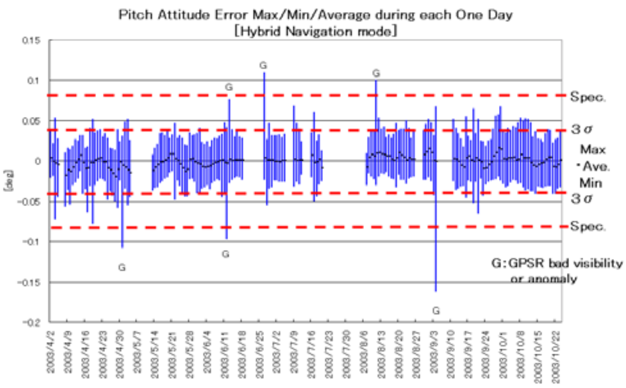

Fig.12.Pitch Attitude Error among each day

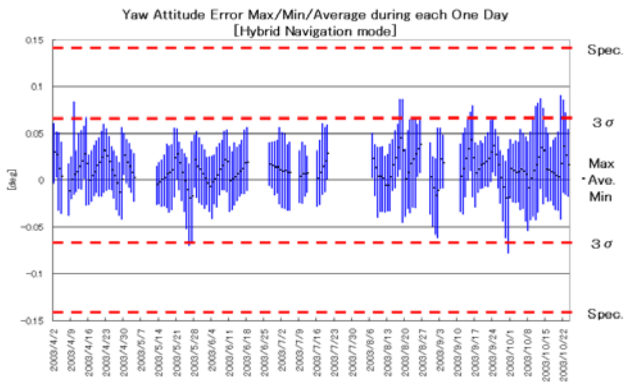

Fig.13. Yaw Attitude Error among each day

4. ESA EVALUATION

As the effect of this correction law was questioned mentioned in section 2.3, the ESA's error is evaluated using the ground estimated attitude. The detailed explanation will be pass on another opportunity as there is no space, the conclusion is as follows. The ESA's seasonal correction law is rather effective especially in pitch axis. Sometimes roll axis is incurred adverse effect, but the correction value is small in such a case. Then using of this correction law is effective totally. The example is shown in Fig.14. The upper figure is ESA error without seasonal correction law, and the lower figure is one with seasonal correction law. It is also turned out that the ESA error depends on the latitude considerably.

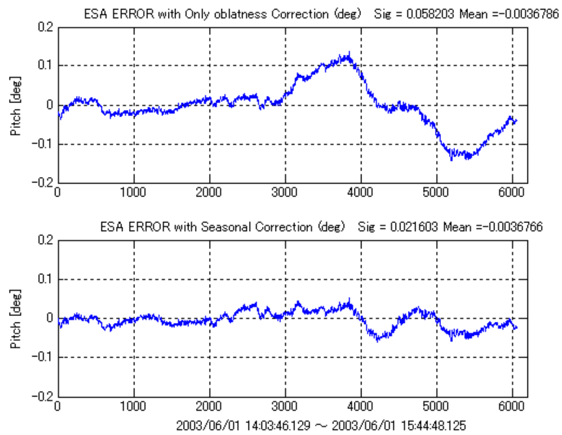

Fig.14. Effectiveness of the Seasonal Correction Law

5. CONCLUSION

We introduce the new method of the onboard attitude determination system "Hybrid Navigation mode" loaded on ADEOS-II, and the ground attitude evaluation and validation of the flight results. The attitude evaluation proves that the hybrid navigation mode overcomes the weaknesses of the conventional navigation mode as we expected, and improves the attitude accuracy fairly. It is verified that the satisfactory attitude have been maintained during the life. On the other hand, the new error sources peculiar to the hybrid navigation mode are turned out at the same time.

ADEOS-II is the first Japanese Earth observation satellite which put the GPSR to practical use for 24 hours. The hybrid navigation mode was developed as an effective utilization of the GPSR, and improved the attitude accuracy successfully. The full-scale attitude evaluation is also the first experience, because the continuous telemetry data of all orbits becomes available for the first time. We have gotten many experiences and have extended our knowledge.

The next Earth observation satellite will carry the star sensor in practical use, and the new very high accurate attitude determination system based on the star sensor will be used. It is thought that the attitude determination system may move to star sensor's system. But the attitude accuracy of the hybrid navigation mode is enough to the global Earth observation satellite. We hope the hybrid navigation mode will be used for the global Earth observation satellite or the backup mode of the high accurate attitude determination system.