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On-Orbit Performance of KOMPSAT-2 Attitude & Orbit Control System

Seung-Wu Rhee
Satellite Future Tech. R&D Division, Korea Aerospace Research Institute
45 Eoeun-Dong, Yuseong-Gu, Daejeon, Korea; 82-42-860-2447
srhee@kari.re.kr

Joo-Jin Lee
Satellite Technology Division, Korea Aerospace Research Institute
45 Eoeun-Dong, Yuseong-Gu, Daejeon, Korea; 82-42-2450
jjlee@kari.re.kr

ABSTRACT

KOMPSAT-2 is the second Korean earth observation satellite after KOMPSAT-1: the 1 meter GSD cartographic capability and it launched in the end of July of 2006 by ROKOT launch vehicle. The dedicated AOCS operational modes are designed for KOMPSAT-2 based on KOMPSAT-1 experience; All of AOCS operational modes requires gyro information. To compensate this drawback, power safe mode is designed and implemented. Successfully AOCS on-board software is developed and extensively verified through a nonlinear simulation process. The simulation results of science fine submode are provided to demonstrate its functionality as well as its performance.

After launching, extensive in-orbit test was performed to validate its functionality and to verify its performances. The in-orbit verification results show AOCS performs very well as expected through nonlinear simulation.

System Overview

KOMPSAT-2 is the second Korean earth observation satellite after KOMPSAT-1 launched successfully in December 1999, which is a high resolution Low Earth Orbit(LEO) satellite that is developed by Korea Aerospace Research Institute(KARI) for the 1 meter panchromatic and 4 meter multi-spectral image data collection. The mission life time of satellite is 3 years. It was launched in July of 2006 by ROKOT launch vehicle and placed into a 685 km sun synchronous orbit(inclination angle is 98.13deg. and mean local time of ascending node is 10:50AM). This type of high resolution imaging mission places stringent requirements on the spacecraft Attitude & Orbit Control System in terms of pointing accuracy, pointing knowledge, rate stability, etc.

The purpose of this paper is to provide an overview of the AOCS design results including the key features of AOCS from the requirement point of view, AOCS operation concept, its design results and on-orbit performances of AOCS.

The structural system of KOMPSAT-2 has hexagonal configuration to maximize internal space. The length of its deployed configuration is about 6.8m and its height is 2.5m. Total mass is about 800kg and the required power is about 1.1kW. The deployed configuration is shown in fig. 1.

KOMPSAT-2 basically consists of three modules: payload module, avionic module, and propulsion module. The payload module is designed to minimize thermal distortion and to securely accommodate a high resolution camera. And its electronic components such as payload management unit, data compression & storage unit, and some of AOCS sensors are located in this module. Most of AOCS components such as reaction wheel assembly, gyro unit, star tracker and associated electronics are mounted in the avionics module. The propulsion module consists of propellant tank, piping system, and 4.45N dual thruster module whose propellant is monopropellant.

KOMPSAT-2 is a 3-axis stabilized spacecraft using zero momentum bias method to provide flexibility in operation and expandability in future program. The attitude information is measured by two star trackers or earth sensors and sun sensors depending on a selected operational mode. Four reaction wheels or four hydrazine thrusters are used to control the spacecraft attitude as well as to maintain an orbit; the pointing accuracy is less than 0.025degree (3 sigma steady state in roll and pitch axes), the pointing knowledge is less than 0.02degree, the orbit position and velocity

information are provided by a GPS receiver. Solar Array Drive Assembly that is a kind of stepping motor, is rotating to face the solar array toward the Sun when spacecraft is nadir-pointing.

The high resolution camera provides 1 meter panchromatic and 4 meter multi-spectral imagery simultaneously. Its image swath is 15km. The size of on-board mass memory storage for image date is about 90Gbits and the transmission rate of image data is 320Mbps through X-band. The detector system employs the push broom imaging technique; the TDI(Time Delay Integration) concept is utilized for PAN imaginary to increase SNR(TDI level of maximum 32).

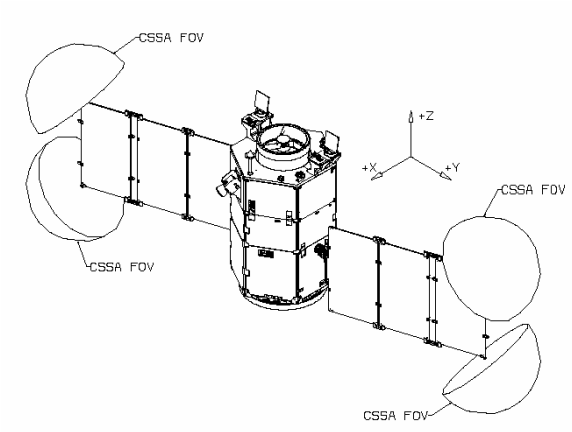

Figure 1: KOMPSAT-2 Deployed Configuration

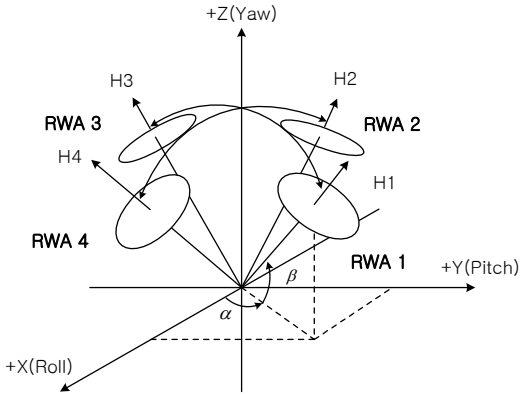

Figure 2: Pyramid Type of Reaction Wheel Configuration

AOCS Overview

The Attitude & Orbit Control System of KOMPSAT-2 is developed based on the highly reliable KOMPSAT-1 spacecraft launched with the 6.6 meter panchromatic camera successfully in the end of 1999 and still now normally operating. Main differences between KOMPSAT-1 and KOMPSAT-2 can be stated as follows: KOMPSAT-2 is employing a strap-down star tracker and gyros to satisfy the stringent requirement of pointing accuracy while KOMPSAT-1 using an earth sensor and gyros for less stringent pointing requirements: 0.15deg(3sigma). From the operational concept point of view, a wheel-based back-up recovery concept is introduced to enhance its operational robustness in addition to the design concept of KOMPSAT-1 whose recovery concept from contingency was designed based on thruster-based control. As a normal operation, gyro sets are autonomously configured by on-board software after spacecraft is separated from launch vehicle. Autonomous gyro selection logic is newly developed for the dedicated KOMPSAT-2 gyro: Northrop Grumman's SIRU whose mechanical and operational concept is totally different from KOMPSAT-1 gyro, Kearfott's TARA gyro. Also, PI-II controller along with Star Tracker based on Kalman filter scheme instead of PI controller used in KOMPSAT-1, is developed and adapted to meet the stringent pointing requirements.

As shown in fig. 1, 4 coarse sun sensors are mounted at the corners of solar array to cover 4 Pi field of view. Fig. 2 shows the installed configuration of 4 reaction wheels arranged in pyramid configuration of $4/\sqrt{3}(1\times1\times1)h$ to provide equally an angular momentum capability to each axis. The 15Nms angular momentum capability and 0.2Nm torque capability of reaction wheel is selected to provide the required maneuvering capability and enough angular momentum capability.

AOCS hardware connection configuration is depicted in fig. 3. As shown in fig. 3, RDU dedicated AOCS on-board Intel processor x386 with math-coprocessor, two star trackers, two earth sensors, three-axis magnetometer, one gyro unit, three magnetic torque rods are interconnected for AOCS functioning properly. Star tracker provides attitude information accurate to within 13 arcsec(3σ) wrt inertia frame while scanning at rates up to 2deg/sec. As usual, a three-axis magnetometer and magnetic torque rods are used for wheel momentum dumping. The sensing range of magnetometer is +/-600mG, and the maximum magnetic dipole moment is 100Am^2. Magnetic torque rods are used to damp out spacecraft rate whenever necessary as well as wheel momentum dumping.

For taking the high resolution camera image, the LOS jitter and rate stability are one of the critical factors to be considered in design phase. In KOMPSAT-2 system, 4 reaction wheels are main source to introduce LOS jitter to the high resolution camera. Thus, micro-

vibration measurement test of RWAs was extensively performed to identify the micro-vibration level that

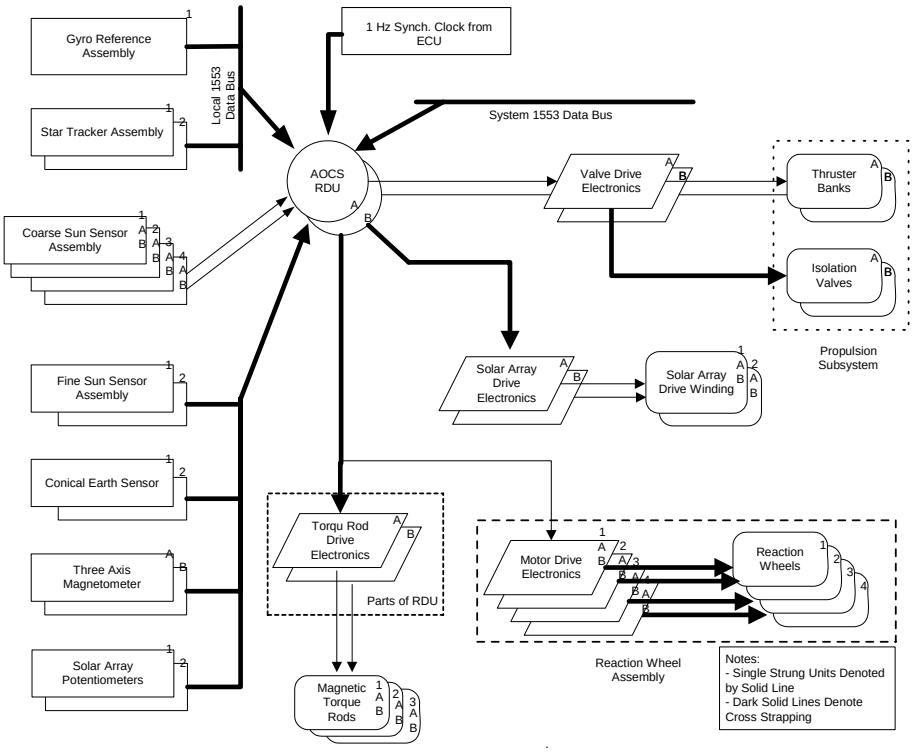

Figure 3: AOCS Hardware Connection Diagram

influences to the system level jitter. Fig. 4 shows the waterfall plot of radial directional force of RWA with respect to the wheel speed as well as frequency ranges.

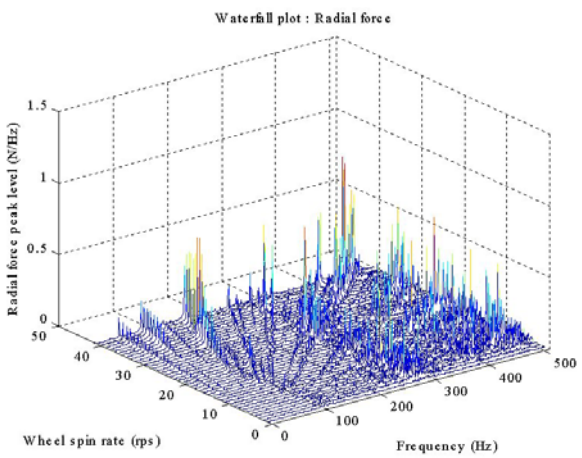

Figure 4: Waterfall Plot of Radial Force of RWA

AOCS Control Modes Design[1]

The AOCS utilizes five distinct modes that consist of ten separate and distinct control submodes; six submodes of them are taken from KOMPSAT-1 heritage and the rest of four submodes are newly developed to provide more operational flexibility as well as robustness to KOMPSAT-2.

Sun Mode

Sun Mode consists of three submodes(Sun Pointing Submode, Earth Search Submode, Safe Hold Submode) that perform different tasks while the spacecraft body is inertially fixed and the arrays are sun-pointing. In all submodes of Sun Mode, the coarse sun sensors and the gyros are the only control sensors and the thrusters are the only control actuators.

Sun Point Submode

This submode provides the capability to point the solar array normal to the sun starting from an arbitrary initial attitude in sunlight. During eclipse transitions, all axes will be held fixed inertially with integrated gyro information. This submode will be used for attitude

stabilization following solar array deployment after launcher speration.

Earth Search Submode

When Earth Search Submode is enabled by the ground command, the AOCS will begin a roll maneuver at a specified rate and automatically transition the spacecraft from Sun Point Submode (two-axis attitude control) to Attitude Hold Submode (nadir pointing attitude, three-axis LVLH control) based on information from the Conical Earth Sensors.

Safe Hold Submode

Safe Hold Submode is functionally equivalent to Sun Point with two exceptions: the gains and deadbands are changed to maximize fuel savings and all redundant equipment (with the exception of gyros) is used in the control loop. The solar arrays will be driven to the initial deployed position.

Maneuver Mode

Maneuver mode consists of two submodes(Attitude Hold Submode, Del-V Submode) that perform different functions while the spacecraft is either inertially fixed or pointed relative to a LVLH reference. In all submodes of Maneuver Mode, the gyros and Conical Earth Sensors as well as Fine Sun Sensors are the control sensors depending on a selected submode, and the thrusters are the only control actuators.

Attitude Hold Submode

This submode provides the capability for three-axis attitude control relative to either an inertial or LVLH reference. Two distinct functions are performed: attitude hold with respect to either reference or attitude maneuvers relative to either reference. When nadir-pointed, the LVLH reference is updated using Conical Earth Sensor(CES) and Fine Sun Sensor(FSS) data. This submode supports entry into Science Mode.

Del-V Submode

This submode provides the capability for three-axis attitude control relative to an inertial or LVLH reference while nominally firing all four thrusters. Attitude control is accomplished by off-modulating the thrusters to counter external disturbance torque.

Science Mode

Science mode consists of two submodes(Science Coarse Submode, Science Fine Submode) that perform similar functions with different sensors for attitude updates while the spacecraft is pointed relative to a LVLH reference. In all submodes of Science Mode, the gyros are used for attitude propagation.

Science Coarse & Fine Submode

The Science Coarse Submode and the Science Fine Submode are functionally identical except that the Science Coarse Submode uses CESs and FSSs while the Science Fine Submode uses Star Trackers for attitude updates: The Science Coarse Submode provides Zero Momentum Bias (ZMB) 3-axis stabilized attitude control using Gyros, CESs, FSSs and RWAs. The nominal attitude in this mode is LVLH reference. Attitude control errors are generated by subtracting the estimated attitude, derived from the propagated gyro reference with updates from CESs and FSSs, from the command attitude derived from On-Board Ephemeris Propagator with GPS data or On-Board Ephemeris Propagator with an uploaded ephemeris data. The roll, pitch and yaw attitudes are actively controlled by reaction wheel torques. Nominally, all four wheels have a bias speed that prevents attitude transients caused by passing through zero wheel speed. In the event of wheel failure, reaction wheels are run about zero nominal bias speed with special software compensation to reduce the effect of transitioning through zero wheel speed.

Back-up Mode

Back-up Mode consists of three submodes(Back-up Sun Pointing Submode, Back-up Earth Search Submode, Back-up Attitude Hold Submode) : two submodes that perform different tasks while the spacecraft body is inertially fixed and the arrays are sun-pointing, and one submode that provides the capability for three-axis attitude control relative to LVLH frame. In all submodes of Back-up Mode, the gyros are used for attitude control.

Back-up Sun Pointing Submode

The Coarse Sun Sensors(CSS) and the gyros are the only control sensors and the reaction wheels are the control actuators. The magnetic torquers are activated for the momentum unloading purpose.

This submode provides the capability to point the solar array normal to the sun starting from an arbitrary initial attitude in sunlight. During eclipse transitions, all axes will be held fixed inertially with integrated gyro information. This submode will be used for attitude stabilization by ground command only.

Back-up Earth Search Submode

The CSSs and the gyros are the only control sensors and the reaction wheels are the control actuators. The magnetic torquers are activated for the momentum unloading purpose.

When Back-up Earth Search Submode is enabled by the ground command, the AOCS begins a roll maneuver at a specified rate and automatically transition the spacecraft from Back-up Sun Point Submode (two-axis attitude control) to Back-up Attitude Hold Submode (nadir pointing attitude, three-axis LVLH control) based on information from the CESs.

Back-up Attitude Hold Submode

The CESs and the gyros are the only control sensors and the reaction wheels are the control actuators. The magnetic torquers are activated for the momentum unloading purpose. No filter estimation is required.

This submode provides the capability for three-axis attitude control relative to LVLH reference using the reaction wheels as the actuator. When nadir-pointed, the roll and pitch axes will be controlled using CES and the yaw axis using the gyro compassing from gyro data. This submode supports entry into Science mode by ground command.

Power Safe Mode

The Tri-Axis Magnetometer(TAM) and the CSSs are the only control sensors and the magnetic torquers are the control actuators. No gyro data is required. This mode is used for attitude stabilization in case that the automated gyro selection logic fails or gyro is malfunctioning during the period of spacecraft deployment as well as normal operational period. Also, once Power Control Unit memory relay associated with Power Safe Mode activation is enabled by ground command, spacecraft will mode-transition to this mode instead of Safe Hold Submode whenever malfunction occurs.

This mode provides the capability to damp out the initial rate of spacecraft and to align the roll axis of spacecraft with the sun vector with the constant roll rate starting from an arbitrary initial attitude in sunlight. During eclipse transitions, the pitch and yaw axes will be held fixed inertially with the constant roll rate.

AOCS Control Mode Transition

Figure 5 describes the AOCS mode transition flow. A2, A3, B2 and B3 paths in figure are newly developed to increase an operational flexibility and robustness for KOMPSAT-2. Note that all the modes except Power Safe Mode requires the spacecraft rate information from gyro. As depicted in figure 6, spacecraft is nadir-pointing in Science Mode and Attitude Submode, and the solar array is pointing to the Sun in Sun Mode and Power Safe Mode.

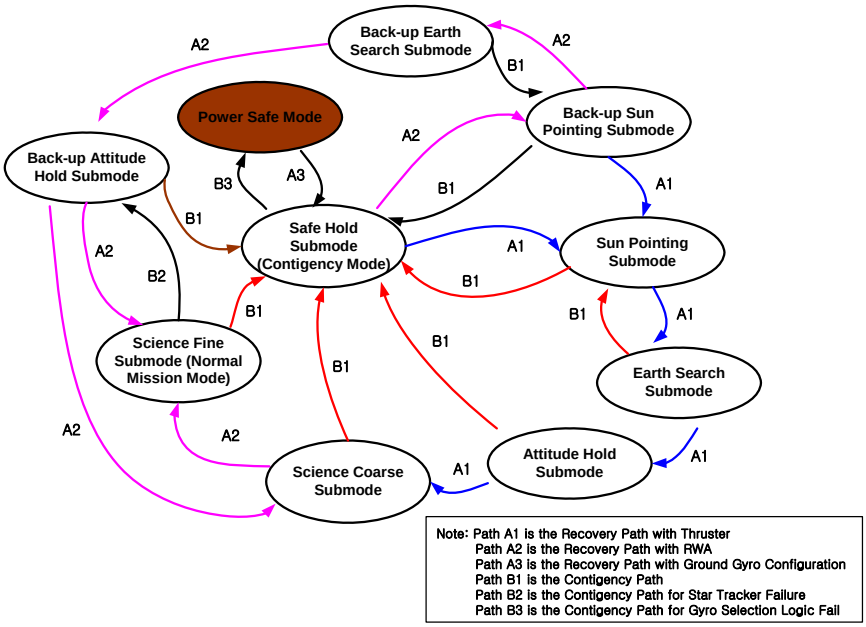

Figure 5: AOCS Mode Transition Diagram

Nonlinear Simulation Results

After designing estimation filter and associated controller, a nonlinear simulation was performed to verify if AOCS performances meet the requirements for high resolution image-taking mission. Fig. 6 shows the simulation result of spacecraft rate that satisfies the rate stability requirement of 0.005deg/sec when solar array rotation stops. When solar array is rotating, spacecraft is excited up to about 0.01deg/sec. by the rotation of solar array as seen in fig. 7. Fig. 8 and 9 show the simulation result of pointing accuracy as well as pointing knowledge. As seen in figures, a pointing accuracy is less than 0.015degree and pointing knowledge less than 0.01degree even though the effect of sensor bias is included in simulation. Some spikes seen in figures are due to the small number of star in star tracker FOV. As shown in fig. 9, the pointing knowledge error is about 0.005deg(3σ) per each axis if a constant bias can be removed. Based this pointing knowledge error, the geolocation error of 61m(CE90) can be obtained, that is less than the requirement of 80m.

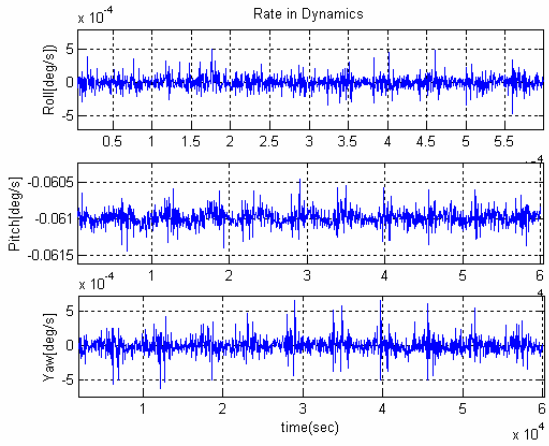

Figure 6: Body Rate in Science Fine Submode with Solar Array Stop

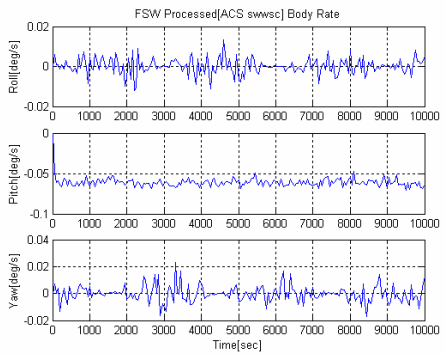

Figure 7: Rate Stability in Science Fine Submode with Solar Array Rotation

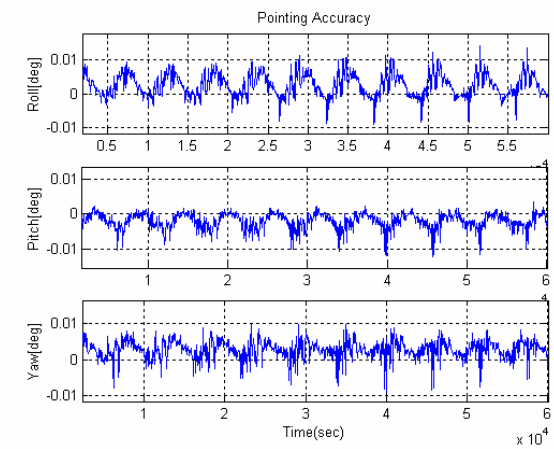

Figure 8: Pointing Accuracy in Science Fine Submode

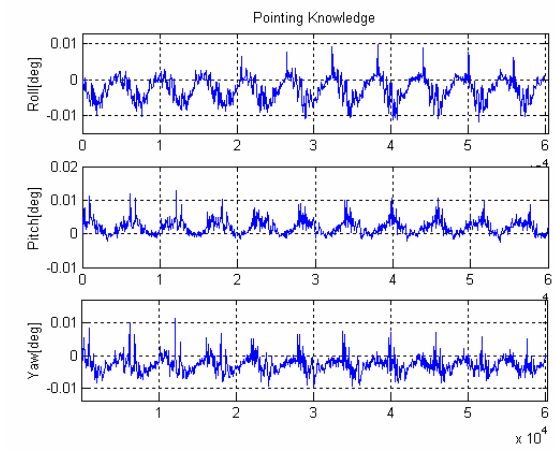

Figure 9: Pointing Knowledge in Science Fine Submode

On-Orbit Performances

KOMPSAT-2 was launched in the end of July, 2006 by ROCKOT launch vehicle. After deploying it in orbit, extensively in-orbit test as well as sensor calibration was performed to verify its performances and improve it: from each component to subsystem performance. According to the in-orbit performance test results, it is verified that AOCS performs as designed.

The in-orbit performance test results show that the pointing accuracy is much less than 0.006 degree in each axis as seen in Fig. 10 while the requirement is 0.025 degree. Fig. 10 and 11 show the rate stability of spacecraft while solar array is rotation to point the Sun. It is seen that the flexibility of solar arrays influences a lot on the rate stability: the rate stability of 0.01deg/sec

was observed from data. However, it is observed the rate stability is less than 0.005deg/sec while the rotation of solar arrays is stopped as seen in fig. 13. Fig. 13 is the rate profiles when spacecraft performs roll-off pointing by 25deg as shown in fig. 14. Fig. 15 shows the profiles of estimated gyro bias for each axis. Generally, the estimated gyro bias in fig. may be due to gyro itself or its misalignment wrt star trackers.

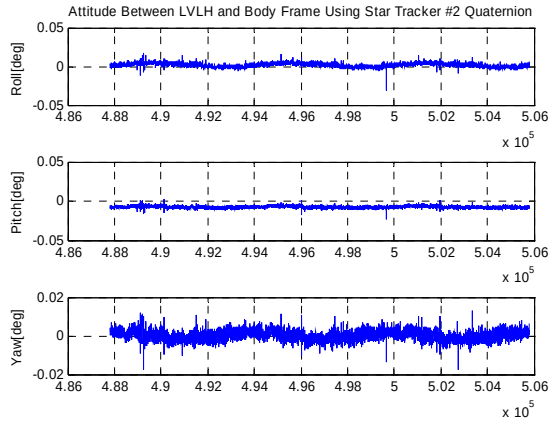

Figure 10: Pointing Performance in Science Fine Submode

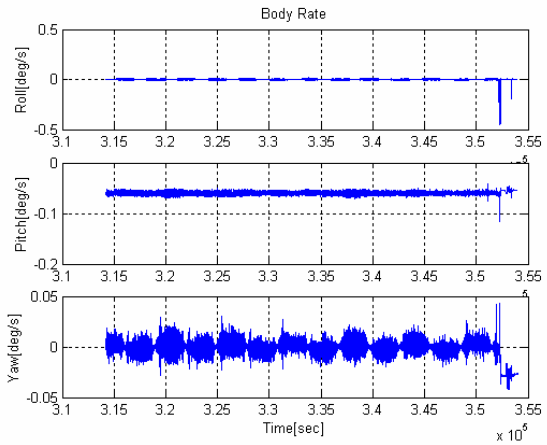

Figure 11: Rate Profile in Science Fine Submode with Solar Array Rotation

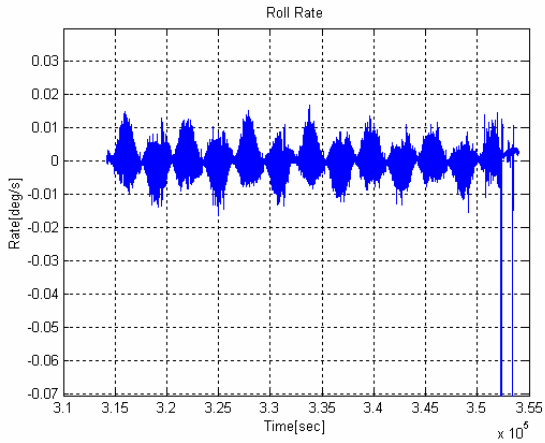

Figure 12: Roll Rate in Science Fine Submode with Solar Array Rotation

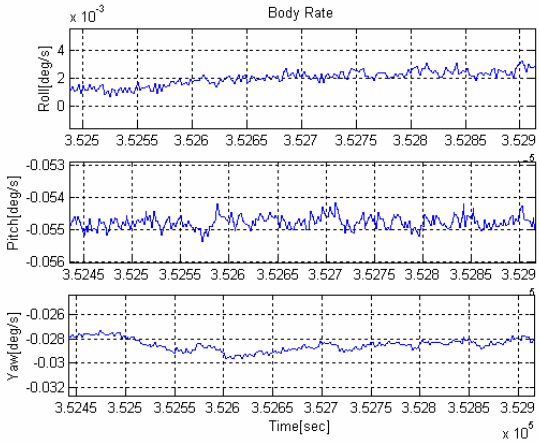

Figure 13: Rate Profile in Science Fine Submode with Solar Array Rotation Stop

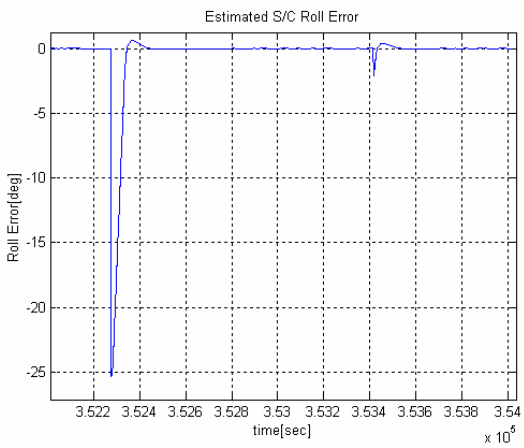

Figure 14: Roll Angle Error Profile during Roll Maneuver

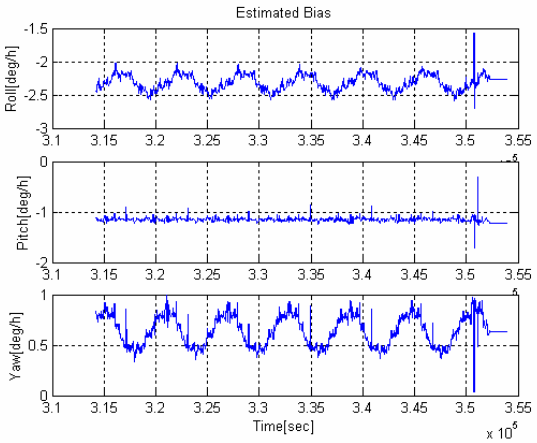

Figure 15: Estimated Gyro Bias in Science Fine Submode

Conclusion Remarks

The AOCS operational concept of KOMPSAT-2 as well as the control logics is successfully developed and implemented to meet the 1 meter high resolution imaging mission requirements. The control algorithm of Power Safe Mode without gyro information is implemented to provide an operational flexibility and to overcome possible malfunction of gyro unit as well as autonomous gyro selection logic. To avoid a burring effect on cartographic image, the pointing stability as well as the micro-vibration effects is considered at AOCS design phase through an extensive test and analysis. As a result of micro-vibration test with RWAs that are main vibration sources, it concludes that system satisfies the jitter requirements. The nonlinear KOMPSAT-2 AOCS simulator imbedded an on-board flight software, is developed to validate the operation sequences of AOCS and to verify the performance of control logics required for successful KOMPSAT-2 mission in Korea. Simulation results show that the LOS rate stability, pointing accuracy and pointing knowledge requirements are satisfied.

After launching, in-orbit test performed successfully and verified AOCS performances that satisfy the specified mission requirements.

Acknowledgements

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