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Magnetic dipole moment estimation and compensation for an accurate attitude control in nano-satellite missions ☆

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ABSTRACT

Nano-satellites provide space access to broader range of satellite developers and attract interests as an application of the space developments. These days several new nano-satellite missions are proposed with sophisticated objectives such as remote-sensing and observation of astronomical objects. In these advanced missions, some nano-satellites must meet strict attitude requirements for obtaining scientific data or images. For LEO nano-satellite, a magnetic attitude disturbance dominates over other environmental disturbances as a result of small moment of inertia, and this effect should be cancelled for a precise attitude control. This research focuses on how to cancel the magnetic disturbance in orbit. This paper presents a unique method to estimate and compensate the residual magnetic moment, which interacts with the geomagnetic field and causes the magnetic disturbance. An extended Kalman filter is used to estimate the magnetic disturbance. For more practical considerations of the magnetic disturbance compensation, this method has been examined in the PRISM (Pico-satellite for Remote-sensing and Innovative Space Missions). This method will be also used for a nano-astrometry satellite mission. This paper concludes that use of the magnetic disturbance estimation and compensation are useful for nano-satellites missions which require a high accurate attitude control.

1. Introduction

Recently nano-satellites have attracted interest because of their practical cost and short development period. Cubesats are 1 kg, 10 cm cubic size satellites, which are developed at several universities. XI-IV and XI-V are examples of the cubesat nano-satellites, which have been developed at University of Tokyo. The mission objectives of the cubesats are technology demonstration and student education [1]. XI-IV has been launched as a first cubesat at University of Tokyo, which took earth images with a small cmos camera successfully, and the satellite has been working properly in orbit more than six years. After the success of these 10 cm cubic size satellites, next nano-satellite missions have been proposed with sophisticated objectives such as remote sensing and observation of astronomical objects. PRISM is a 8.5 kg nano-remote sensing satellite, which was proposed as a next nano-satellite project after the cubesats. The mission objective is to obtain 30 m resolution images in 8.5 kg nano-satellite. In order to achieve the mission requirement, the telescope orientation should be controlled to the earth, and the satellite attitude should be stabilized to an accuracy of 0.7 deg/s. To satisfy the attitude requirements, the satellite used the gravity gradient torque which is caused from an extensible boom. In this mission, several attitude disturbances should be reduced for the attitude control [2,3]. The attitude disturbances on a satellite in low earth orbit (LEO) result from the gravity gradient, atmospheric drag, solar pressure, and magnetic torque. For the PRISM mission, the

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Nomenclature

J	objective function
M	residual magnetic moment of a satellite
s	scale factor of a sensor
b	bias error of a sensor
IGRF(x,t)	function to calculate the geomagnetic field. Parameters are satellite position and time
B	geomagnetic field vector
x,y,z	satellite position in a reference frame
t	time
$\mathbf{M_v}$	magnetometer voltage before analog digital conversion
$\mathbf{C_{bi}}$	direction cosine matrix from a reference to a body frame
ω	angular velocity of a satellite attitude
I	moment of inertia of a satellite
h	angular momentum of a reaction wheel
x	predicted state vector
A, **B**	system matrices for a Kalman filter
w	process noise
v	observation noise
$\mathbf{\Phi},\mathbf{\Gamma}$	state transition model matrices
P	predicted estimate covariance
z	measurement vector
Q	system noise covariance
K	Kalman gain

Subscript

g, **m**	Gyro and magnetometer, respectively.
b, **i**	Body frame and reference frame, respectively.
ref	Reference.

magnetic disturbance is dominant and can cause attitude instability. Because of the magnetic torque, the satellite is difficult to control the telescope direction to the earth using only the gravity gradient torque.

Nano-JASMINE (Nano-Japan Astrometry Satellite Mission for INfrared Exploration) is also a nano-satellite planned as a nano-astrometry satellite at University of Tokyo in cooperation with the National Astronomical Observatory of Japan (NAOJ) [4,5]. The main objective of the mission is to measure the three-dimensional positions of stars in our galaxy using the parallax of stars. In order to obtain accurate astrometry data, the satellite should be stabilized to better than 4×10^{-7} rad/s, which is difficult to achieve using only a feed back controller because of the magnetic disturbance [6,7].

During nano-satellite missions, the magnetic torque is the dominant disturbance and the main source of the attitude instability. In this paper, the effect of the magnetic disturbance for an accurate attitude control in the nano-satellite missions are presented, then the paper proposes a new method to estimate the residual magnetic moment using an extended Kalman filter in orbit. The paper also proposes a method to calibrate a gyro sensor and a magnetometer for an accurate estimation of the magnetic moment. In this paper, Sections 1 and 2 show overview of the PRISM mission and the effects of the magnetic disturbance. Sections 3 and 4 propose a method to estimate the magnetic dipole moment and in orbit performance of the compensation. Finally, this method will be applied for our next nano-satellite Nano-JASMINE in Section 5.

2. Nano-remote sensing satellite PRISM

2.1. Overview of the PRISM mission

PRISM is a 8.5 kg nano-remote sensing satellite, which was developed at University of Tokyo. Main objective of the PRISM mission is to obtain 30 m resolution images. In order to obtain high resolution earth images, conventional remote sensing satellites have to contain optical system with multiple lenses or reflection mirrors to fold the long focal length within the structure. Such system requires stiffness of the structure, which induces the increase of mass (Table 1).

In order to reduce the total mass of the telescope, PRISM uses an extensible boom for optical system (Fig. 1). The structure consists of flexible materials which can be extended by only the internal elastic force. Any mechanical actuators are not needed for extension of the boom. These features of the flexible extensible boom enable to design a very compact, light-weight optics system.

Table 1
Comparison of PRISM with previous remote sensing satellites.

Year	Satellite	Resolution (m)	Mass (kg)
1991	UoSat-5	2000	48
1999	UoSat-12	10	312
2002	AlSat	32	90
2004	TopSat	2.5	110
2008	**PRISM**	**30**	**8.5**

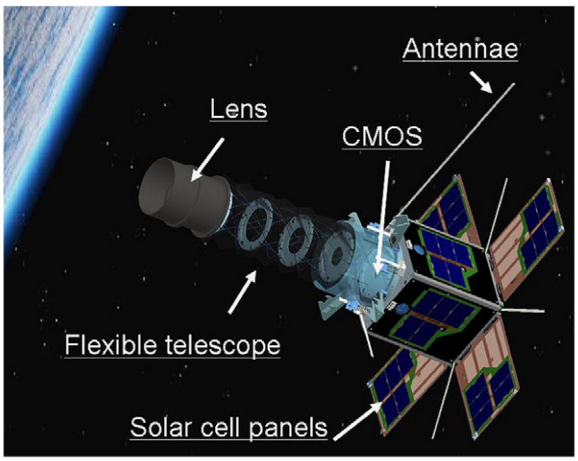

Fig. 1. Overview of the PRISM satellite.

Table 2 shows the specification of the PRISM satellite. PRISM has been launched into Sun-Synchronous LEO. In the PRISM satellite, three types of micro-processors are installed, SH7145F as a main processor, H8-3048 for the communication subsystem, and PIC-16F877 for the power subsystem. These processors are connected to each other by Can-Bus interfaces, which has high reliability in space strict environment. The communication subsystem consists of a Tx module and two Rx modules. The Tx module has two radio modules, AFSK 1200 bps and GMSK 9600 bps. The AFSK module is mainly used for downlink of house-keeping data, such as the history of temperature and current sensors. The GMSK module has eight times higher communication rate than the AFSK module. These communication systems enable to downlink of image and telemetry data rapidly.

2.2. Attitude determination and control system for the PRISM mission

The exposure time of the NAC is 0.1 ms to obtain earth images. This exposure time requires better than 0.7 deg/s attitude stability to achieve 30 m resolution images in the mission. The satellite attitude should be stabilized to better than 0.7 deg/s during observation, and the telescope orientation should be controlled to the earth. In the design phase of the project, the attitude was intended to be controlled passively using only the gravity gradient torque after the boom extension. As shown in the previous section, the satellite is difficult to control attitude using only passive attitude control because of the magnetic torque. To satisfy the mission requirements, the attitude is determined by sun sensors and magnetometers and controlled actively by MTQs. Table 3 shows the specifications of the ADCS sensors and actuators. In the PRISM, the attitude is determined using the sun sensors and the magnetic sensors, which provide attitude information in the body frame. The geomagnetic field vector and the sun direction vector in a reference frame can be calculated with the onboard computers. The geomagnetic field vector in the reference frame is calculated by the IGRF (International Geomagnetic Reference Field) model using lower than fourth order terms. In order to calculate the IGRF model, the satellite position is calculated by an orbital propagator. Orbit parameters for the propagation are uploaded from a ground station in every week. The attitude is determined by the TRIAD algorithm and can be estimated more accurately using an extended Kalman filter, and the attitude is controlled using the Bdot and the cross product control method [8,9].

Table 2
Specification of the PRISM satellite.

Size	$192 \times 192 \times 400$ mm
Mass	8.5 kg
Mission	Remote sensing
Orbit	Sun-synchronous orbit
ADCS	Magnetometer, Sun sensor, MTQ
CPU	SH7145, H8-3048, PIC-16F877

Table 3
Specifications of the ADCS sensors and actuators.

Gyro sensor	Tsukasa21	
	Range	-60.0 to 60.0 deg/s
	Accuracy	0.1 deg/s
Magnetometer	AMI 201	
	Range	$-20\,000.0$ to 20 000.0 nT
	Accuracy	500 nT
Sun sensor	home-build	
	FOV	100 deg $\times$ 100 deg
	Accuracy	1 deg
MTQ	home-build	
	Range	-0.3 to 0.3 Am^2
	Accuracy	0.05 Am^2

3. Effects of the magnetic disturbance in the PRISM mission

In the PRISM mission, the compensation of the residual magnetic moment improves an attitude pointing and stabilization accuracy. Following subsections present the effects of the magnetic disturbance in the PRISM mission.

3.1. Attitude pointing accuracy

PRISM should satisfy the attitude control requirements, which are to control the telescope toward the earth and stabilize the attitude during observation. These requirements can be achieved by the attitude determination using magnetometers and sun sensors, and the cross product attitude control method using MTQs. If the magnitude of the magnetic disturbance is smaller than the gravity gradient torque, the passive attitude control using the gravity gradient torque can be effective to keep the telescope direction toward the earth. Table 4 shows the attitude disturbance torques in the PRISM mission. As shown in Table 4, the magnetic disturbance is dominant and causes the attitude instability.

Fig. 2 shows a simulation result of the passive control using the gravity gradient torque when the residual magnetic moment is 0.1, 0.01, 0.001, and 0.0001 Am^2, respectively. In this simulation, the satellite controls the attitude toward the earth using only the gravity gradient torque. The theta in Fig. 2 is defined as the angle between the direction of the telescope and the earth. The theta should be controlled to zero in order to get earth images in the mission. Fig. 3 shows a simulation result of the attitude disturbances during the simulation of Fig. 2, when the residual magnetic moment is 0.1 Am^2. The simulation results show that the satellite is difficult to achieve the requirements using only the gravity gradient torque, if the

Table 4
Attitude disturbance in the PRISM mission.

Item	**Value** (Nm)
Magnetic disturbance	3.0×10^{-6}
Gravity gradient	8.0×10^{-7}
Air pressure	3.0×10^{-8}
Solar pressure	1.0×10^{-8}

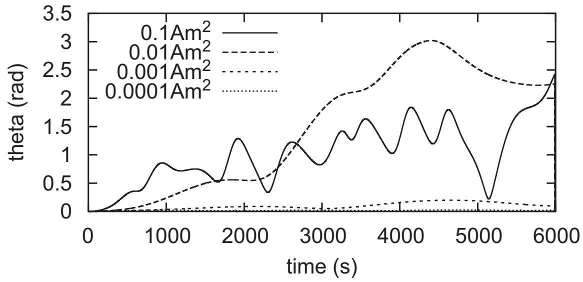

Fig. 2. Simulation results of passive attitude control using only the gravity gradient torque.

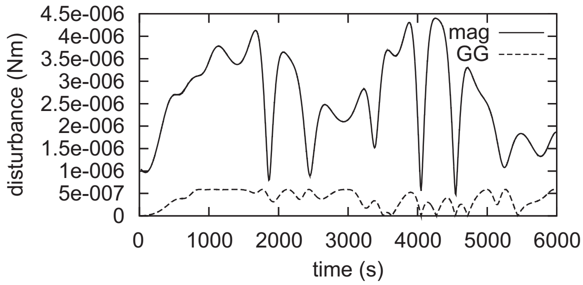

Fig. 3. Simulation result of the attitude disturbances.

residual magnetic moment is larger than 0.1 Am^2. With the 0.01 Am^2 magnetic moment, the magnitude of the magnetic disturbance becomes almost the same to that of the gravity gradient torque. In PRISM, the extended boom is installed for folded optical system, which courses asymmetry of the moment of inertia after the boom extension. Because the moment of inertia around *z*-axis is relatively smaller than the other axes, this asymmetry can cause the gyro-effect around *z*-axis easily. During passive control phase, the *z*-axis spins up because of the small inertia around *z*-axis and the relatively large magnetic disturbance. The *z*-axis obtains large angular velocity which causes the gyro-effect. This causes the spin-axis, namely *z*-axis in this case, to be almost fixed in the inertial frame. As a result, the satellite cannot keep the telescope orientation toward the earth passively. The theta, which is the angle between the telescope direction and the earth, almost changes in an orbital period because of this effect with the 0.01 Am^2 RMM in Fig. 2. With the 0.1 Am^2 RMM, the effect of the magnetic torque is stronger than the effect of the gyro-effect which is caused from the *z*-axis spin rate. As a result the theta changes more rapidly than the orbital period because of stronger magnetic disturbance. In order to achieve the requirement passively, the magnetic disturbance should be reduced to 0.001 Am^2 as shown in Fig. 2.

Table 5 shows measurement of the residual magnetic moment of PRISM on the ground. This measurement has been conducted for each satellite components without power supplies. Table 5 shows that the antenna and battery have relatively large magnitude of the residual magnetic moment. Total residual magnetic moment is 0.06 Am^2 excluding magnetic moment caused from current loops

Table 5
Magnetic moment of the satellite components.

Item	**Value** Am^2
Antenna	0.02
Battery	0.03
Total	0.06

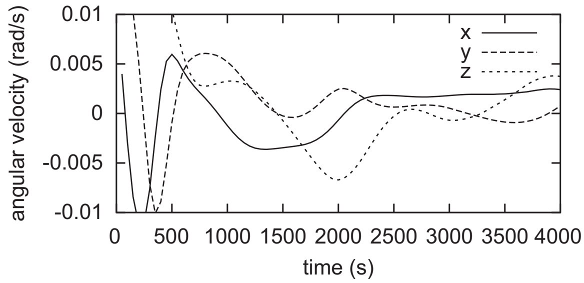

Fig. 4. Simulation result of the attitude stabilization without the magnetic disturbance compensation.

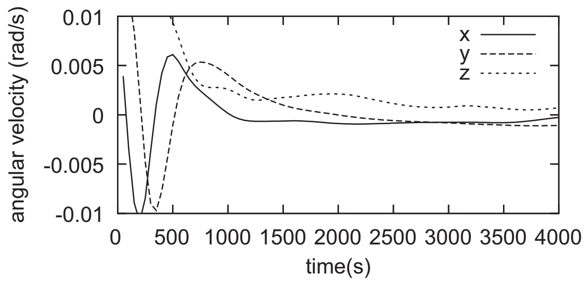

Fig. 5. Simulation result of the attitude stabilization with the magnetic disturbance compensation.

of the components and solar batteries. This result and Fig. 2 show that the satellite is difficult to control the attitude passively using the gravity gradient torque to achieve the requirement without the compensation of the magnetic disturbance.

3.2. Attitude stabilization accuracy

In order to achieve 30 m resolution images in the PRISM mission, the satellite attitude should be stabilized to better than 0.7 deg/s, which is achieved by the Bdot attitude control method using MTQs, and the requirement can be achieved without magnetic compensation [8]. For more accurate attitude control for extra missions, the effect of the magnetic disturbance should be canceled, and this compensation method is useful to achieve attitude control requirements. Figs. 4 and 5 show simulation results of the attitude stabilization using the Bdot method with the magnetic compensation and without the magnetic compensation, respectively. In Fig. 5, the magnetic moment is compensated using magnetic torquer to an accuracy of 1×10^{-3} Am^2. The simulation results show that the attitude is stabilized more precisely with the magnetic compensation. The compensation of the magnetic disturbance is useful for precise attitude control in nano-satellite missions.

4. Estimation of magnetic dipole moments and in orbit performance

As shown in the previous section, the residual magnetic moment (RMM) compensation is useful for improving an attitude control accuracy. In order to cancel the magnetic disturbance by applying counteracting magnetic torque using MTQs, the magnetic dipole moment should be estimated accurately. The methods for estimation of the RMM are presented in this section. Fig. 6 shows overview of the method to estimate the magnetic dipole moment. The RMM is estimated with the geomagnetic field and angular velocity information which are obtained from magnetometers and gyro sensors, respectively. The data usually contains a scale factor and a bias error, which cause large estimation errors. The effect should be canceled for highly accurate magnetic dipole moment estimation, which can be achieved by estimation using least square methods. Following subsections show the method to cancel the effects of the sensor noises and how to estimate the RMM.

4.1. Method for calibration of sensors

In PRISM, the gyro sensor and magnetometer are calibrated on the ground, and bias and scale factor errors are estimated from telemetry data more precisely in orbit. Structures on which sensors are mounted guarantees misalignment errors better than 1°, and misalignment estimation is not indispensable for the requirements. This subsection shows how to estimate the bias and scale factor of the gyro and magnetometer in the PRISM mission.

Firstly, the bias and scale factor error of the magnetometer are estimated using a least square method. In this estimation, the IGRF is used as reference information. Intrinsically, the norm of the geomagnetic field calculated by the IGRF should agree with that of the magnetometer measurement. Fig. 7 shows that the norm of the IGRF disagree with that of the magnetometer measurement because of the bias and scale factor errors in PRISM telemetry data. Using this disagreement, the bias and scale factor error can be estimated by the least square method on the ground station. In this estimation, the objective function **J** is written as follows:

$$\mathbf{J}(\mathbf{s_m},\mathbf{b_m}) = \sum_{\mathbf{k}=0}^{\mathbf{N}} (|\mathbf{IGRF}(\mathbf{x},\mathbf{y},\mathbf{z},\mathbf{t})_\mathbf{k}| - |\mathbf{B}(\mathbf{s_m},\mathbf{b_m})_\mathbf{k}|)^2, \tag{1}$$

where x, y, z are satellite position in the reference frame. The satellite position can be calculated using the two line elements and the SGP4 algorithm. $IGRF(x,y,z,t)$ is a function

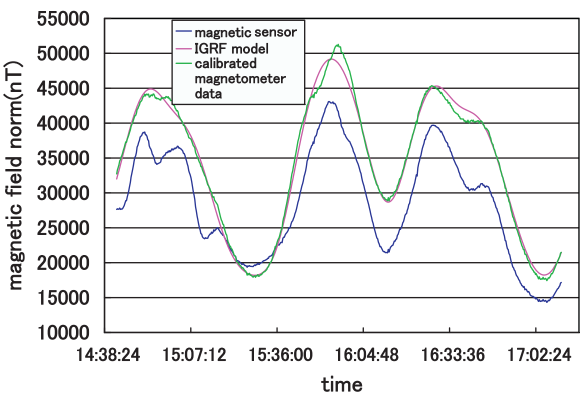

Fig. 7. Result of the scale factor and the bias noise estimation of the magnetic sensor using telemetry data.

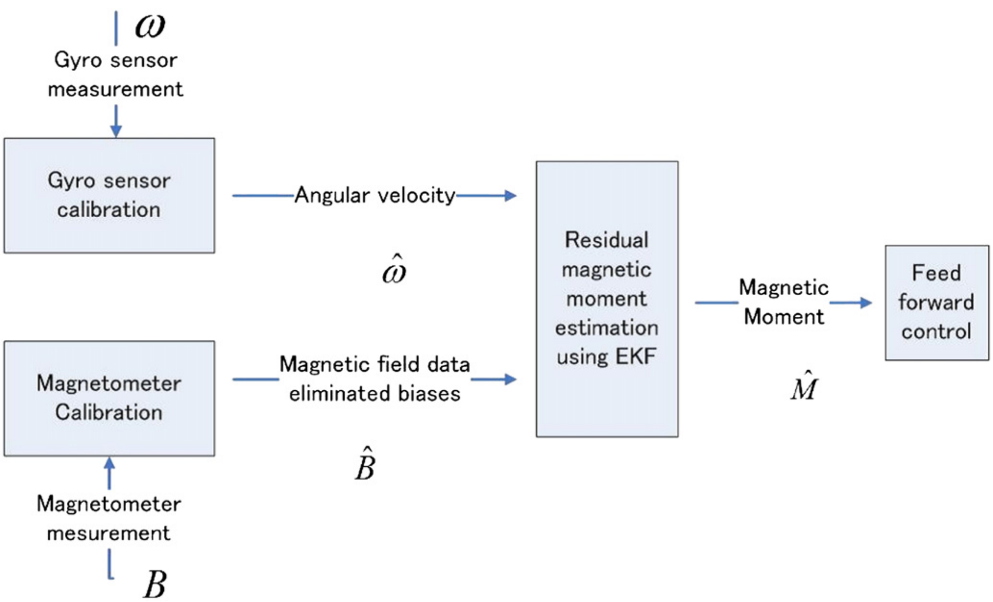

Fig. 6. Strategy for magnetic dipole moment estimation.

to calculate the geomagnetic field using the IGRF model. $\mathbf{s_m}$, $\mathbf{b_m}$ are the scale factor and bias noise of a magnetometer, respectively. The magnetometer measurements are modeled as follows:

$$\mathbf{B} = \mathbf{s_m}\mathbf{M_v} + \mathbf{b_m}, \tag{2}$$

where $\mathbf{B}$, $\mathbf{s_m}$, $\mathbf{M_v}$, and $\mathbf{b_m}$ are magnetometer measurement, scale factor, magnetometer voltage before analog digital conversion, and bias noise, respectively. Objective of the method is to estimate the scale factor $\mathbf{s_m}$ and the bias noise $\mathbf{b_m}$, which can be achieved by minimizing the function J in Eq. (1).

Fig. 7 shows a result of this magnetometer calibration using telemetry data from the PRISM. In Fig. 7, the norm of calibrated magnetometer measurement vector is fit to that of the IGRF, which shows the bias and scale factor are estimated and corrected. After obtaining magnetometer parameters, bias and scale factor of a gyro sensor are estimated using the following equation:

$$\mathbf{C_{bi}}\frac{\mathbf{dB_i}}{\mathbf{dt}} = \frac{\mathbf{dB_b}}{\mathbf{dt}} + \omega \times \mathbf{B_b}, \tag{3}$$

where $\mathbf{C_{bi}}$ is the direction cosine matrix (DCM) from the reference frame to the body frame, $\mathbf{B_i}$ and $\mathbf{B_b}$ are the geomagnetic field vector in the reference frame and the body frame, respectively. Because $\mathbf{B_i}$ changes periodically in orbital period (about 6000 s), which is relatively low frequency, time derivation of the geomagnetic field vector can be treated as zero as follows:

$$\frac{\mathbf{dB_i}}{\mathbf{dt}} \sim 0. \tag{4}$$

Derivation of the geomagnetic field in the reference frame is treated as constant in short time in this method. Thus, Eq. (3) can be written as follows:

$$\frac{\mathbf{dB_b}}{\mathbf{dt}} = -\omega \times \mathbf{B_b}. \tag{5}$$

In this equation, the vector $\mathbf{dB_b}/\mathbf{dt}$ should agree with the vector $-\omega \times \mathbf{B_b}$. Fig. 8 shows comparison between $\mathbf{dB_b}/\mathbf{dt}$ and $-\omega \times \mathbf{B_b}$ using PRISM gyro telemetry data and calibrated magnetometer measurement. This figure shows the vectors, $\mathbf{dB_b}/\mathbf{dt}$ and $-\omega \times \mathbf{B_b}$, disagree each other because of the bias and scale factor errors of the gyro sensor. Using this disagreement, the bias and scale factor errors of the gyro sensor are estimated by a least square method. Objective function $\mathbf{J}$ is expressed as follows:

$$\mathbf{J}(\mathbf{s_g},\mathbf{b_g}) = \sum_{k=0}^{N}\left(\frac{\mathbf{dB_k}}{\mathbf{dt}} - \mathbf{B_k} \times \omega_\mathbf{k}(\mathbf{s_g},\mathbf{b_g})\right)^{\mathbf{2}}, \tag{6}$$

where $\mathbf{s_g}$, $\mathbf{b_g}$ are the scale factor and bias noise of the gyro measurement. These parameters are estimated with the minimized function $\mathbf{J}$.

Fig. 8 shows a result of the calibration in the PRISM mission. The vector $-\omega \times \mathbf{B_b}$ is fit to the vector $\mathbf{dB_b}/\mathbf{dt}$, and this figure shows that the scale factors and bias noise are estimated. From these calibrations, the RMM can be estimated more precisely.

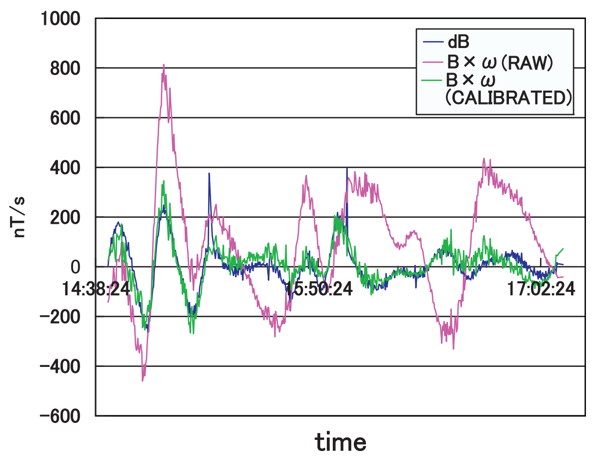

Fig. 8. Result of the scale factor and bias noise estimation of the gyro sensor using PRISM telemetry data.

4.2. Magnetic dipole moment estimation

This subsection presents the estimation method for a RMM using an extended Kalman filter. A model of attitude dynamics can be expressed as follows:

$$\mathbf{I}\dot{\omega} = \mathbf{M} \times \mathbf{B} - \omega \times (\mathbf{I}\omega + \mathbf{h}) - \dot{\mathbf{h}}, \tag{7}$$

where $\mathbf{I}$ is the moment of inertia, $\mathbf{h}$ is the angular momentum of reaction wheels, $\mathbf{M}$ is a RMM, and $\mathbf{B}$ is the geomagnetic field, respectively. State vector can be expressed as follows:

$$\mathbf{x} = \mathbf{x_{ref}} + \Delta\mathbf{x}, \tag{8}$$

$$= \begin{pmatrix} \omega_{\mathbf{ref}3\times1} \\ \mathbf{M}_{\mathbf{ref}3\times1} \end{pmatrix} + \begin{pmatrix} \Delta\omega_{3\times1} \\ \Delta\mathbf{M}_{3\times1} \end{pmatrix}. \tag{9}$$

Because the attitude dynamics equation is non-linear, the equation is linearized around $\mathbf{x_{ref}}$, and $\Delta\mathbf{x}$ is treated as the state vector. The linearized system equation can be expressed as follows:

$$\Delta\dot{\omega} = \mathbf{I}^{-1}([(\mathbf{I}\omega_\mathbf{ref} + \mathbf{h})\times] - [\omega_\mathbf{ref}\times]I)\Delta\omega - \mathbf{I}^{-1}([\mathbf{B}\times]\Delta\mathbf{M}), \tag{10}$$

which can be arranged in matrix form as

$$\mathbf{x} = \begin{pmatrix} \Delta\omega \\ \Delta\mathbf{M} \end{pmatrix}, \tag{11}$$

$$\mathbf{A} = \begin{pmatrix} \mathbf{I}^{-1}([(\mathbf{I}\omega_\mathbf{ref} + \mathbf{h})\times] - [\omega_\mathbf{ref}\times]\mathbf{I}) & [-\mathbf{I}^{-1}\mathbf{B}\times] \\ \mathbf{O}_{3\times3} & \mathbf{O}_{3\times3} \end{pmatrix}, \tag{12}$$

$$\mathbf{B} = \begin{pmatrix} \mathbf{E_{3\times3}} & \mathbf{O_{3\times3}} \\ \mathbf{O_{3\times3}} & \mathbf{E_{3\times3}} \end{pmatrix}, \tag{13}$$

where a skew-symmetric matrix $[\mathbf{a}\times]$ is defined as follows:

$$[\mathbf{a}\times] = \begin{pmatrix} 0 & -a_z & a_y \\ a_z & 0 & -a_x \\ -a_y & a_x & 0 \end{pmatrix}. \tag{14}$$

The time update equations can be written as follows:

$$\hat{\mathbf{x}}_\mathbf{k}^{-} = \mathbf{\Phi_{k-1}}\hat{\mathbf{x}}_\mathbf{k-1} + \mathbf{\Gamma_{k-1}}\mathbf{w_{k-1}}, \tag{15}$$

$$\mathbf{P_k^-} = \mathbf{\Phi_{k-1}}\mathbf{P_{k-1}}\mathbf{\Phi_{k-1}^T} + \mathbf{\Gamma_{k-1}}\mathbf{Q_{k-1}}\mathbf{\Gamma_{k-1}^T}, \tag{16}$$

where $\mathbf{\Phi\Gamma}$ can be expressed as follows:

$$\mathbf{\Phi_k} = \mathbf{e^{A\Delta T}}, \tag{17}$$

$$\mathbf{\Gamma_k} = \left(\int \mathbf{e^{A\Delta T}} \mathbf{d}\tau \right) \mathbf{B}. \tag{18}$$

Observation equation is expressed as follows:

$$\mathbf{z_k} = (\mathbf{E_{3\times3}} \;\; \mathbf{O_{3\times3}})\mathbf{x_k} + \mathbf{v_k}. \tag{19}$$

Measurement update equations are calculated as follows:

$$\mathbf{K} = \mathbf{P_k^- H_k^T R_k^{-1}}, \tag{20}$$

$$\hat{\mathbf{x}}_\mathbf{k} = \hat{\mathbf{x}}_\mathbf{k}^- + \mathbf{K_k}(\mathbf{z_k} - \mathbf{H_k}\hat{\mathbf{x}}_\mathbf{k}^-), \tag{21}$$

$$\mathbf{P_k} = \mathbf{P_k^-} - \mathbf{P_k^- H_k^T}(\mathbf{H_k P_k^- H_k^T} + \mathbf{R_k})^{-1}\mathbf{H_k P_k^-}. \tag{22}$$

Fig. 9 shows a result of the magnetic dipole moment estimation using the extended Kalman filter with PRISM telemetry data. The estimated value is (-0.057, -0.026, -0.033 Am^2) in x, y, and z axes, respectively. And the magnitude of the estimated magnetic moment almost agrees with the magnetic moment measurement on the ground (Table 4). This estimated value has been uplinked to the satellite for the magnetic compensation.

4.3. Early in orbit performance

After estimating the magnetic dipole moment, the method for compensation of the magnetic disturbance has been examined in order to assess how accurate the RMM was estimated in PRISM. Estimated RMM has been uplinked to the satellite. Figs. 10 and 11 show history of the angular velocity with the compensation and without the compensation, respectively. In the telemetry data, the satellite attitude was not controlled with any active attitude controller. Fig. 10 shows the telemetry data without the compensation of the magnetic disturbance. In this case, the attitude is stabilized to better than 0.7 deg/s, however, the attitude becomes unstable because of the magnetic disturbance. Fig. 11 shows the telemetry data with the compensation of the magnetic disturbance. In this figure, the satellite is more stable and achieves 0.1 deg/s accuracy. In the body frame, the geomagnetic field changes approximately in orbital period, which causes periodical change of angular velocity in low frequency as shown in Figs. 10 and 11. Amplitude of the angular velocity depends on the magnitude of the RMM of the satellite, approximately. The amplitude of the angular velocity is 0.008 and 0.002 rad/s in Figs. 10 and 11, respectively. From these telemetry data, the RMM has been reduced roughly to one forth. From the consideration, the result obtained shows that estimation error is about 0.01 Am^2 in the experiment.

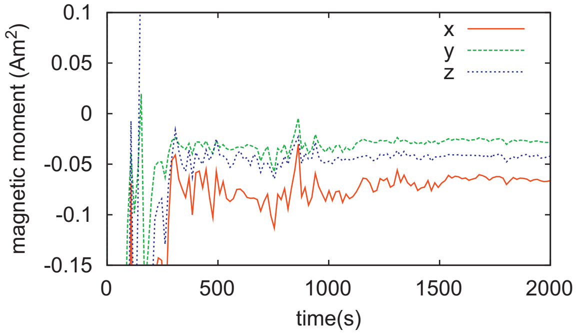

Fig. 9. Estimation of the RMM using the extended Kalman filter.

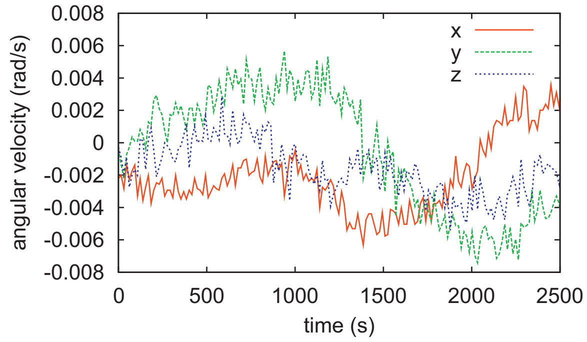

Fig. 10. Telemetry data of the angular velocity without the magnetic compensation.

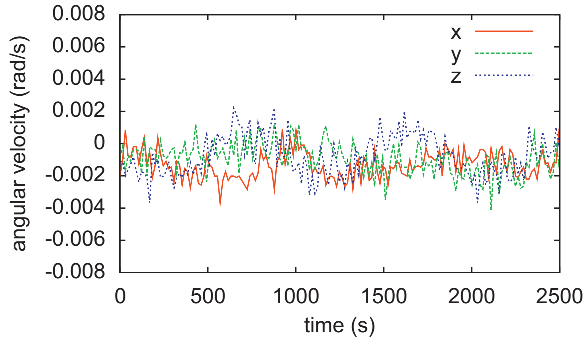

Fig. 11. Telemetry data of the angular velocity with the magnetic compensation.

5. Application of the RMM compensation for the Nano-JASMINE mission

Nano-JASMINE (Nano-Japan Astrometry Satellite Mission for INfrared Exploration) is a 30 kg astronomy satellite, which is developed at the ISSL, University of Tokyo (see Fig. 12). Objective of the mission is to measure the three-dimensional positions of stars to an accuracy of 1.8 mas (milli-arcsecond). In order to obtain accurate astrometry data, the satellite should be stabilized to better than 4×10^{-7} rad/s, which is difficult to achieve using only conventional sensors and feed back controllers.

For the Nano-JASMINE mission, the magnetic disturbance is dominant because efforts can be made during design process to minimize the disturbances from the other sources, the gravity gradient, the air pressure, and the solar pressure, which depends on mass property, but because the magnetic disturbance depends on current loops in onboard electronics, it is difficult to compensate on the ground. Table 6 shows the approximate magnitude of the expected disturbance torque in the Nano-JASMINE mission.

In the Nano-JASMINE mission, the magnetic disturbance should be canceled for the following two reasons,

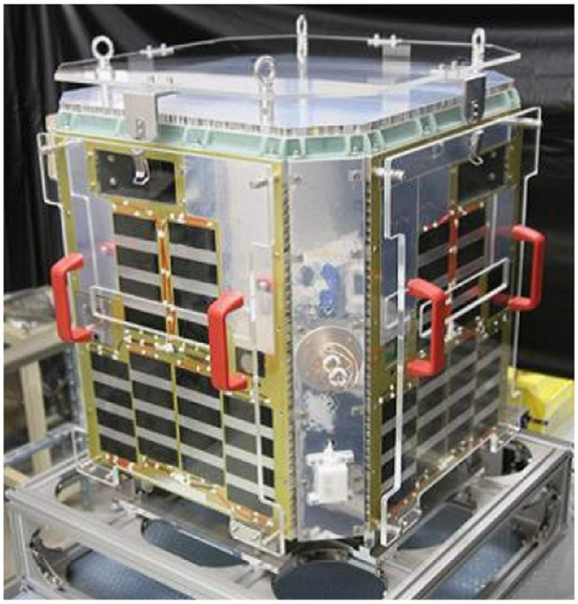

Fig. 12. Overview of the Nano-JASMINE mission.

Table 6
Attitude disturbance in the Nano-JASMINE mission.

Disturbance	Magnitude (Nm)
Magnetic	1.0×10^{-6}
Air	3.0×10^{-9}
Solar pressure	1.0×10^{-9}
Gravity gradient	3.0×10^{-9}

to satisfy the attitude stability requirement and the requirement for the observation period. Firstly, Nano-JASMINE cannot stabilize the attitude because of the magnetic disturbance to a required accuracy (4×10^{-7} rad/s). The magnetic disturbance compensation is indispensable for the mission requirement during observation. Fig. 13 shows a simulation result to stabilize the attitude using only a feedback controller, when the RMM is 0.1 Am^2. In this simulation, the satellite is assumed to use the star trackers (STT) and fiber optical gyros (FOG) to determine the attitude and reaction wheels to control the attitude. If the magnetic disturbance is not compensated, the attitude cannot be stabilized to less than 1×10^{-5} rad/s, which is the requirement for mission telescope star acquisition. Secondly, the Nano-JASMINE should keep stabilizing attitude for more than 30 orbital periods from mission requirements, which is more difficult with the magnetic disturbance because of the angular momentum saturation of the reaction wheels. Fig. 14 shows angular momentum of the RWs. With the magnetic disturbance, the period of the observation phase becomes shorter, because the reaction wheels obtain the angular momentum rapidly, and unloading operation is needed more frequently. From the mission requirements, the satellite should stabilize the attitude about 30 orbital period. This means the magnetic disturbance should be suppressed using actuators except the RWs.

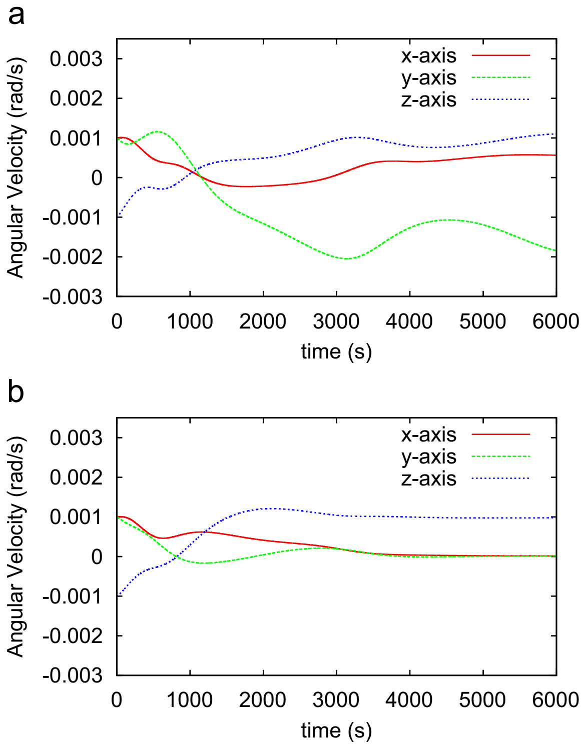

Fig. 13. Simulation results of the attitude stabilization, (a) without magnetic disturbance compensation, (b) with magnetic disturbance compensation.

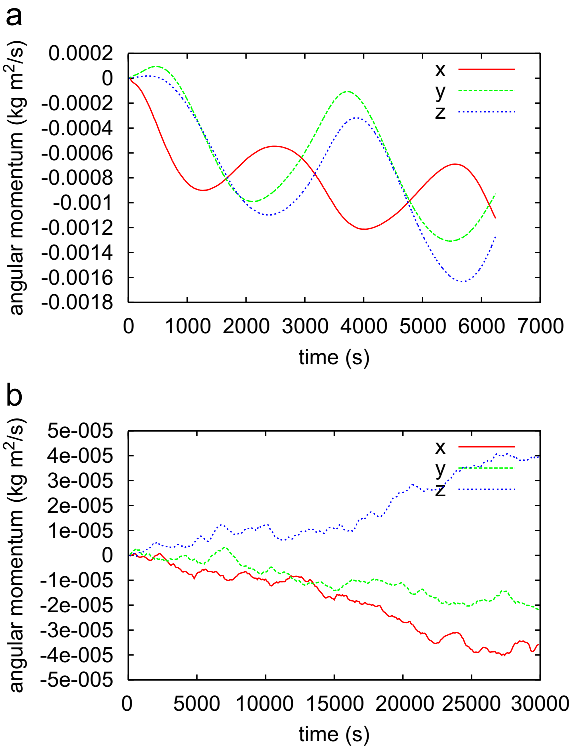

Fig. 14. Simulation result of RW angular momentum, (a) without magnetic disturbance compensation, (b) with magnetic disturbance compensation.

From these reasons, the magnetic disturbance should be canceled by MTQs. Compensation of the magnetic moment is useful and indispensable for the Nano-JASMINE mission.

6. Conclusions

This research considers the attitude control system for the nano-remote sensing satellite PRISM, focusing on effects of an attitude magnetic disturbance and compensation of the effects for an accurate attitude control. The mission objective is to obtain 30 m resolution images in an 8.5 kg nano-satellite mission. For the mission objective, PRISM should control the direction of the telescope to the Earth and stabilize the attitude better than 0.7 deg/s, which are difficult to achieve using only the gravity gradient torque because of the magnetic disturbance. In this research, the magnetic dipole moment is estimated using telemetry data with an extended Kalman filter and canceled by applying a counteracting magnetic torque based on estimated value. For accurate estimation of the magnetic moment, effects of sensor noise should be canceled before the estimation. These measurement noises are estimated by least square methods in the PRISM mission. In orbit, the RMM have been estimated to an accuracy of 0.01 Am^2. This method is applicable for low earth orbit nano-satellites which should achieve accurate attitude control requirements. This paper shows the attitude control system for the nano-astronomy satellite Nano-JASMINE as an example. In this mission, the attitude should be stabilized to better than 4×10^{-7} rad/s, which is difficult to achieve without the compensation of the magnetic disturbance. The method is also useful for management of the angular momentum for reaction wheels. This research concludes that the use of the magnetic disturbance estimation and compensation are useful for nano-satellites missions which require a high accurate attitude control.

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