

Attitude Control System Performance Estimation for Next Generation Small Satellite 1

*Son-Goo Kim¹⁾ and Jang-Soo Chae²⁾

^{1), 2)} Satellite Technology Research Center, KAIST, Daejeon 305-701, Korea

¹⁾ kimsongoo@kaist.ac.kr

ABSTRACT

In this paper, we present the performance estimation results of attitude control system (ACS) of Next Generation Small Satellite 1 (NEXTSat-1). The main goal of NEXTSat-1 is to validate the national space core technologies in on-orbit and to support science mission payloads operation. To support the various payloads and spacecraft bus operation with respect to the mission requirements, NEXTSat-1's ACS should provide extended performance capabilities for attitude control, stability, and system estimation therefore precise system modeling and reliable performance estimation is necessary in design step. From basic sensors and actuators modeling to noise effectiveness induced due to internal or external combined disturbances are analyzed and overall system pointing performances are presented through simulation studies. Finally, we address that the pointing performances of NEXTSat-1 satisfy the system requirements as well as payload requirements.

1. INTRODUCTION

NEXTSat-1 project is one of the satellite technology development programs in the big science category with national research fund. This project kicked off at the Jun. 2012.

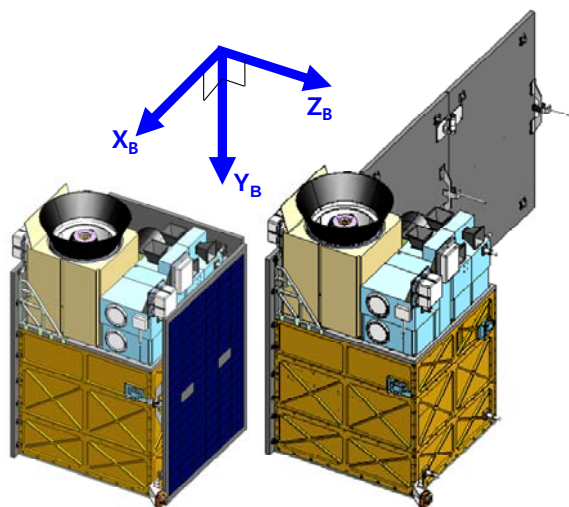


Fig. 1 ACS Configuration of NEXTSat-1

NEXTSat-1 is unique satellite program in many ways from Science and Technology Satellite (STSAT) series that was developed before in same satellite development program. The development strategies of NEXTSat-1 include: 1) standardization, 2) low power consumption, 3) miniaturization, 4) modularization. These paradigm has purpose to improve international competitiveness at the small satellite development technology as well as progress reliability of space core technologies through or-orbit test and validation [1]. Moreover, another goal of this project is jacking up the technological independence ratio by localizing a few key fundamental technologies, design know-how, and electrical parts. No less important goal is the training of manpower who will be experts in the space science and aerospace engineering fields. Main missions of NEXTSat-1 include: 1) space core technology validation, 2) identifying the exact cause of the space storm from detection of space radiation, plasma analyzing, and ionosphere observation, 3) close examination of the beginning, evolutionary progress of galaxy, and star formation history. A number of research institutions and universities participate in this project for space mission payloads development. National space core technologies are consist of high speed data processing system, 3-dimension mass memory, S-band digital transponder, fiber optic gyroscope, star tracker. Science mission payloads are comprised of Instrument for the Study of Space Storm (ISSS) and Near-Infrared Spectrometer for Star Formation History (NISS). NEXTSat-1 is also equipped with register jet thruster so that orbit transition will be performed for precise orbit correction. Satellite bus is built by SaTReC, KAIST with extensive space-oriented technologies and satellite development know-how. Table. 1 shows the main requirements of the satellite.

Table. 1 NEXTSat-1 Main Requirements

Item	Requirements	Performance
Orbit	650~800 km	Sun-synchronized orbit
Mass	100 kg (more or less)	Bus : 60 kg Payloads : < 50 kg
Mission Life	2 years	2 years
Attitude Control	3-axis stabilization	Pointing Accuracy: < $\pm 0.04^\circ$
Power	250 W (EOL)	> 250 Watt
Bus Voltage	+24 ~ +32 V	+24 ~ +32 V
Bus Comm. Interface	CAN Bus	500 Kbps
Bus/Payloads Comm. Interface	Serializer / Deserializer LVDS	Bus: Serializer, Payloads: deserializer
TC/TM transmission	S-Band	Uplink / Downlink adjustable
Science Data transmission	X-band	16 Mbps

Key objective of ACS is support the payloads and satellite bus operation to meet the mission requirements. As the science payloads require high pointing accuracy and stability performances, an enhanced microsatellite NEXTSat-1 carries sophisticated

attitude control system for small satellites. ACS comprise of the variable sensors, actuators: Two coarse sun sensors, two three-axis magnetometer, star tracker, four fiber optic gyros, four reaction wheels, three electro magnetic torque bar, inertial measurement unit, GPS receiver.

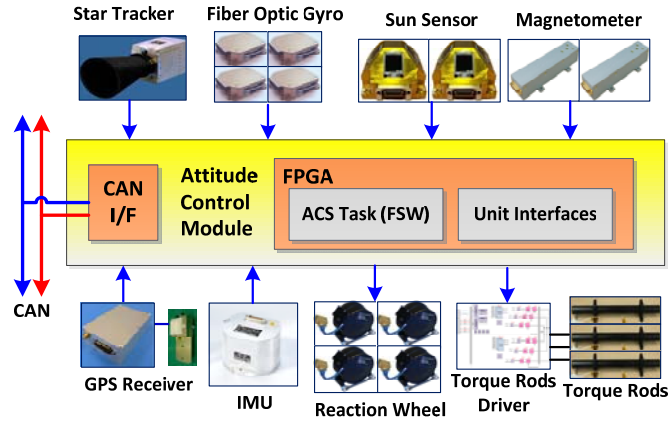


Fig. 2 Attitude Control System Configurations

To support the science mission, especially for NISS, ACS should provide pointing accuracy up to ± 0.04 degree (2σ , RMS) and ± 18 arc second (1σ , RMS) pointing stability. Other payload's requirements are not too tight compare with spacecraft pointing performance so that ACS needs to mainly concern the required stability of NISS. The paper is organized as follows. First, the basic modeling of main sensors and actuators are introduced and estimate performance of each model. Next, main attitude estimator (Unscented Filter) and controller (Quaternion Feedback) are addressed followed by orbit analysis and environmental disturbance. Finally, all simulation results are presented for final pointing budget analysis.

2. Sensor/Actuator Modeling

In this section, the analytical modeling of main sensors and actuators are introduced and simulation results of each model are presented to figure out those validities.

2.1 Gyro Modeling

A common sensor that measures the angular rate is a rate-integrating gyro. A widely used model is given by

$$\begin{aligned}\tilde{\omega} &= \omega + \beta + \eta_v \\ \dot{\beta} &= \eta_u\end{aligned}\tag{1}$$

where $\tilde{\omega}$ is measured angular rate, ω is true angular rate, β is drift, and η is independent zero mean gaussian white noise processes with

$$\begin{aligned} E\{\eta_v(t)\eta_v^T(\tau)\} &= I_{3 \times 3} \sigma_v^2 \delta(t-\tau) \\ E\{\eta_u(t)\eta_u^T(\tau)\} &= I_{3 \times 3} \sigma_u^2 \delta(t-\tau) \end{aligned} \quad (2)$$

where $\delta(t-\tau)$ is dirac delta function. After doing simple calculations, the discrete time rate and bias equation is given by

$$\begin{aligned} \tilde{\omega}_{k+1} &= \omega_{k+1} + \frac{1}{2}[b_{k+1} + b_k] + \left[\frac{\sigma_v^2}{\Delta t} + \frac{1}{12} \sigma_v^2 \Delta t \right]^{\frac{1}{2}} N_v \\ b_{k+1} &= b_k + \sigma_v \Delta t^{\frac{1}{2}} N_u \end{aligned} \quad (3)$$

The type of gyroscope of NEXTSat-1 is fiber optic and manufacturer is LITEF GmbH in Germany. The noise parameters are given by $\sigma_u = 1.393 \times 10^{-7} \text{ rad/sec}^{3/2}$ and $\sigma_v = 2.901 \times 10^{-5} \text{ rad/sec}^{1/2}$. The initial biases for each axis of gyro are given by 3 deg/hr in constant temperature. Fig. 3 show the bias estimates, which is well estimated by the Unscented Kalman Filter.

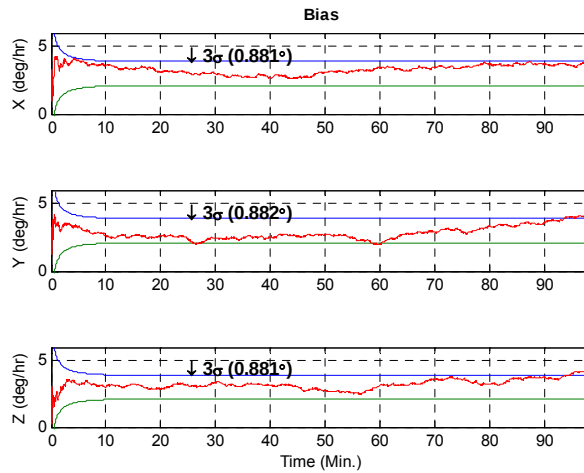


Fig. 3 Fiber Optic Gyro Bias Estimates

2.2 Star Tracker Modeling

Basic Modeling

Analytical pin-hole camera model is a base of star tracker modeling. The image plane coordinates of star is given by

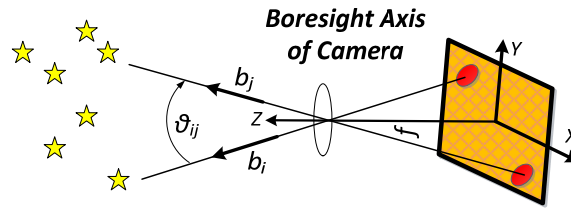


Fig. 4 Pine-Hole Camera Model

$$\begin{aligned} x_j &= f \frac{C_{11}r_{x_j} + C_{12}r_{y_j} + C_{13}r_{z_j}}{C_{31}r_{x_j} + C_{32}r_{y_j} + C_{33}r_{z_j}} + x_0 \\ y_j &= f \frac{C_{21}r_{x_j} + C_{22}r_{y_j} + C_{23}r_{z_j}}{C_{31}r_{x_j} + C_{32}r_{y_j} + C_{33}r_{z_j}} + y_0 \end{aligned} \quad (4)$$

where f is focal length and (x_0, y_0) is principal point offset from center of detector. Then the measurement unit vector is followed by

$$b_j = \frac{1}{\sqrt{x_j^2 + y_j^2 + f^2}} \begin{Bmatrix} -(x_j - x_0) \\ -(y_j - y_0) \\ f \end{Bmatrix} \quad (5)$$

The relationship between measurement b_j (image space) and their projection r_j (inertial frame) is given by

$$b_j = Cr_j + v_j \quad (6)$$

where C is direction cosine matrix between image and inertial frame and v is zero mean Gaussian white noise which satisfies $E\{v_j\} = 0$, $E\{v_j v_j^T\} = \sigma_j^2 [I_{3 \times 3} - (Ar_j)(Ar_j)^T]$. For the complete vector sensor, the observed vector at time t_k, b_k is related to the reference vector r_k according to

$$b_k = Ar_k + v_k \quad (7)$$

The measurement $\tan \alpha$ and $\tan \beta$ are uncorrelated. The covariance of these two quantities is determined as following

$$R_z = \frac{1}{1 + c(z_1^2 + z_2^2)} \begin{bmatrix} (1 + cz_1^2)^2 & (cz_1 z_2)^2 \\ (cz_1 z_2)^2 & (1 + cz_2^2)^2 \end{bmatrix} \quad (8)$$

Note that this is approximately correct since it makes the covariance matrix a random quantity. Finally the quaternion estimator (QUEST) measurement model agrees well with the inferred measurement model for the real sensor.

$$R_z^{QUEST} = \sigma_{w_k}^2 (1 + z_1^2 + z_2^2) \begin{bmatrix} 1 + z_1^2 & z_1 z_2 \\ z_1 z_2 & 1 + z_2^2 \end{bmatrix} \quad (9)$$

The detector is Star1000 (CMOS) sensor and has 1024 by 1024 pixels. Field of view of star sensors is set to $18^\circ \times 18^\circ$ and its data update rate is 10 Hz maximum. The noise equivalent pixel error is expected up to 0.2 pixel and this value is equivalent to 12.65 arc seconds (3σ) angle error. From the noise parameters, the performance simulation results is showing below. Simulation time is 1 hour and performed with J2000 star catalogue.

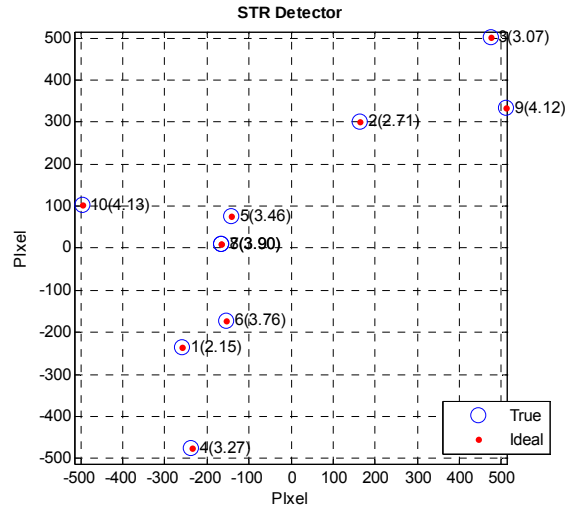


Fig. 5 Probability Density of Measured Star

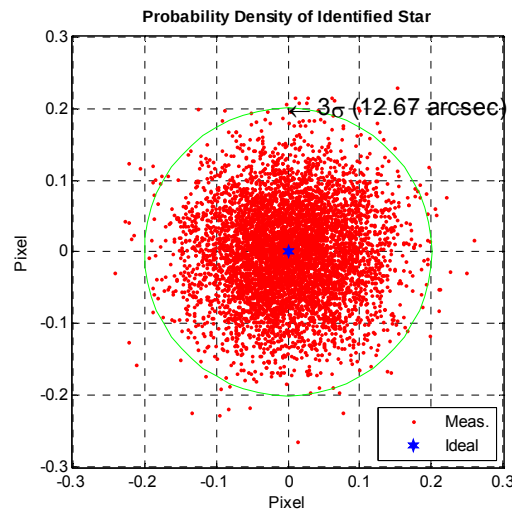


Fig. 6 Identified Star Position on Detector

Fig. 5 shows simulated identified star position on the detector. 10 stars are detected with respect their brightness. Fig. 6 shows that probability density of one measured star. As we see that the 3 sigma error boundary of a measured star shows 12.67 arc seconds noise value and this result is almost same with the input noise parameter. With this star sensor model, the noise equivalent angle (NEA) is calculated

from QUEST algorithm. QUEST knowledge results for each axis present in Fig. 7. X, Z axis has nearly 4 arc seconds knowledge error and these values are most significant because to satisfy the requirement of pointing accuracy for NISS payload operation. The bore-sight of star tracker is aligned with $-Y$ axis of satellite body so that the Y axis error is much bigger than the result of other axis.

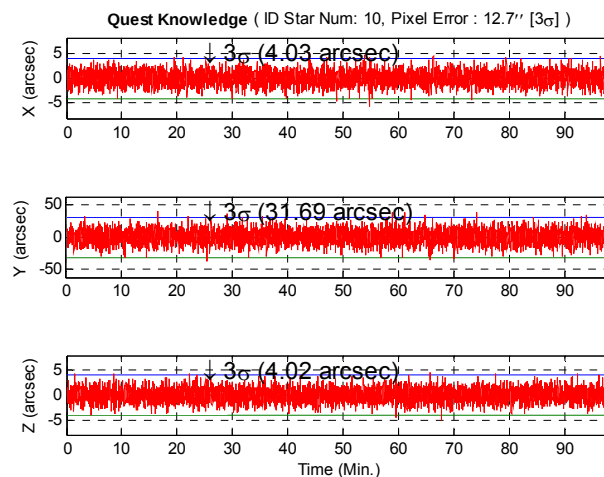


Fig. 7 QUEST Results

Thermal Distortion Analysis

In on-orbit, spacecraft bus undergoes thermal variation and it effects to unit performances especially attached on the spacecraft outside. In the case of star tracker, thermal distortion is one of the big error sources so that this error should be analyzed and compensated through environmental test. We have done a thermal distortion analysis for NEXTSat-1's star tracker and got a series of error number table. Distortion happen star tracker's body itself and a contact surface between star tracker and spacecraft body. Body structural residual distortions are and contact surface residual distortions are . The process of structural distortion analysis is not shown here for brevity but the low frequency errors are simulated with the error parameters and the results are shown below.

Fig. 8 shows an identified star's locus on the detector. The position of a star is moving less than 0.08 pixels magnitude due to thermal variation so that makes iterative elliptic locus. Quest knowledge results with thermal distortion are shown in Fig. 9. As we see clearly, the knowledge error show a kind of low frequency fluctuation during 100 minutes simulation time and the magnitude increased up to ± 2.5 arc seconds compare with the results of ideal condition.

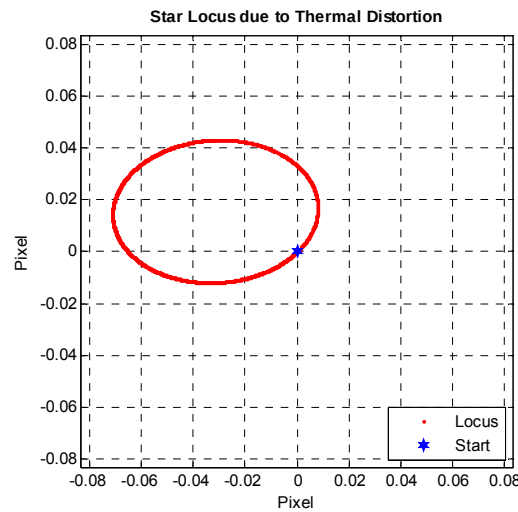


Fig. 8 Thermal Distortion Effect

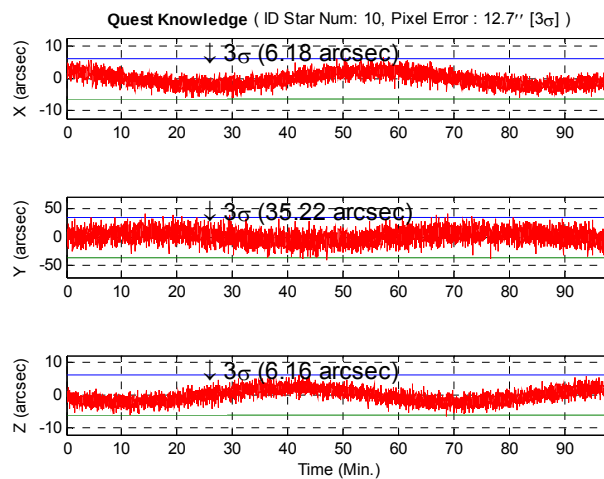


Fig. 9 QUEST Results with Thermal Distortion Effect

2.3 Reaction Wheel Modeling

NEXTSat-1's reaction wheel assembly (RWA) is suitable to microsatellite control and its manufacturer is Rockwell Collins Deutschland in Germany. RWA has 0.12 Nms angular momentum and wheel speed is limited at 3000 rpm. Reaction torque is 5mNm at 2800 rpm which is operational speed range. NEXTSat-1 has 4 RWAs and these are arranged in pyramid configuration and their momentum directions in satellite body coordination are given matrix below and followed by realized torque profile with respect to angular momentum

$$[RW_1, RW_2, RW_3, RW_4]_B = \begin{bmatrix} -0.5773 & -0.5773 & 0.5773 & 0.5773 \\ -0.5773 & 0.5773 & -0.5773 & 0.5773 \\ 0.5773 & -0.5773 & -0.5773 & 0.5773 \end{bmatrix}_B \quad (10)$$

RWA torque command is generated by following sequence.

- I. Once required torque is acquired, the torque value is break up to each RWA with respect to its configuration.
- II. Calculate current RWA's angular momentum.
- III. Calculate available RWA's torque from current angular momentum (based on the data in Fig. 10)
- IV. Each RWA torque command is clamped again by maximum torque, 5 mNm.

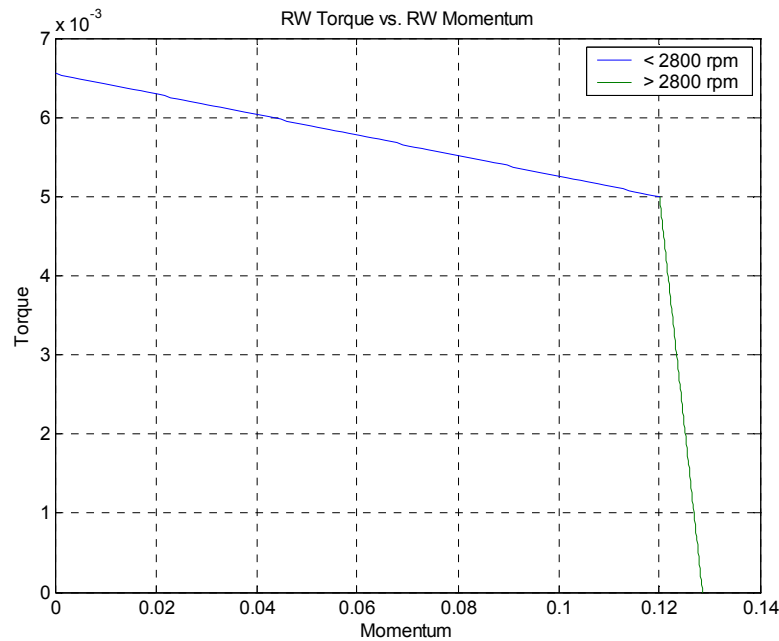


Fig. 10 RW Torque vs. RW Angular Momentum

3. Pointing Budget Analysis

In this section, we synthesize whole analysis results and provide final pointing budget with initial attitude parameter setting. To calculate pointing knowledge, unscented kalman filter (UKF) is used as an attitude estimator. UKF will be used as a main attitude determination algorithm in normal operation. Fig. 11 shows a schematic of the typical attitude estimation flow with various satellite sensors.

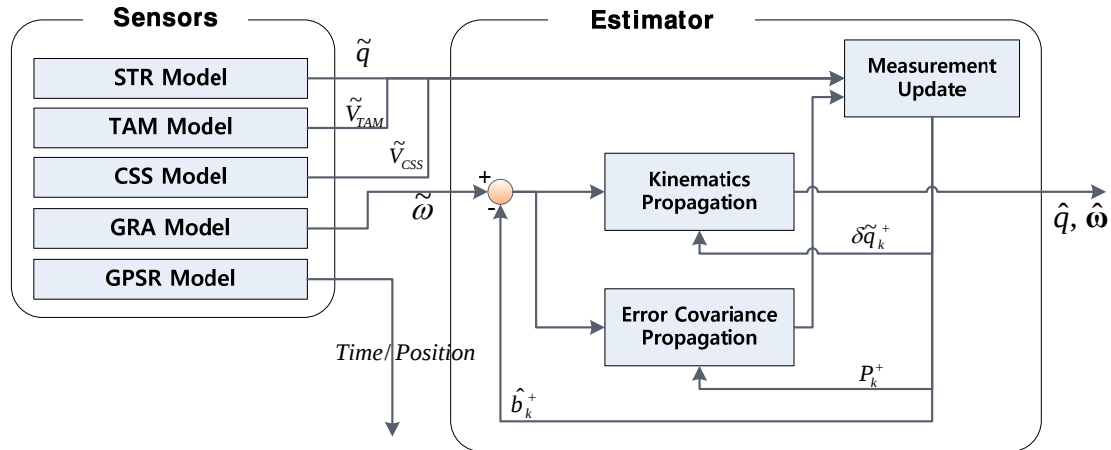


Fig. 11 Attitude Determination Flow

For the initial parameter value, settling time, natural frequency, and damping ratio of spacecraft is given by $T_s = 30 \text{ sec}$, $\xi = \sqrt{2}/2$, and $\omega_n = -\log(0.05)/\xi/T_s \text{ rad/sec}$. The moment of inertia of satellite body is followed by

$$J_{\text{deployed}} = \begin{bmatrix} 11.012 & 0.457 & 0.776 \\ 0.457 & 8.627 & 1.076 \\ 0.776 & 1.076 & 12.763 \end{bmatrix} \text{ kg} \cdot \text{m}^2 \quad (11)$$

We use quaternion feedback methods that is given by

$$\text{Control Torque} = -[K]\delta q - [D]\delta \omega \quad (12)$$

where proportional gain and derivative gain is given by $K = J \cdot \omega_n^2$ and $D = J \cdot 2.0 \cdot \xi \cdot \omega_n$ and the euler angles of spacecraft are set to $[X, Y, Z]_B = [0, 0, 0] \text{ deg}$ and angular velocities are also set to zero for all axis. Fig. 12 shows that the pointing knowledge budget using star tracker and gyro measurements. X, Z axis knowledge is less than ± 0.003 (2σ) degrees and Y axis value is less than ± 0.005 (2σ) degrees which are satisfy the top requirement of satellite system. The bore sight of STR is co-aligned with $-Y$ axis of satellite.

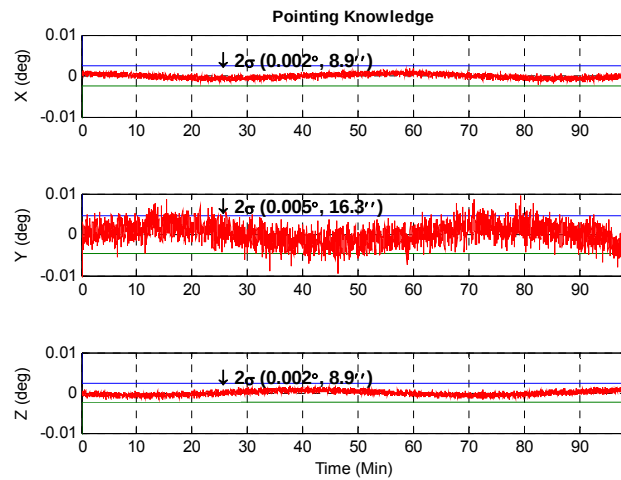


Fig. 12 Pointing Knowledge Results

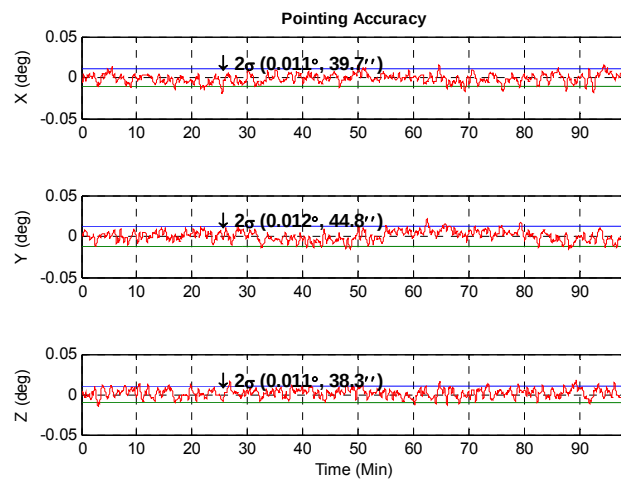


Fig. 13 Pointing Accuracy Results

Fig. 13 present the pointing accuracy with external disturbances and actuator's jitter noise. The accuracy of all axis shows less than ± 0.02 (2σ) degrees which is definitely satisfying the top requirements. Fig. 14 shows peak to peak pointing stability results in 12 seconds period. NISS, the science mission payload, require less than 18 arcsec (1σ , RMS) resolution during 12 seconds optics exposure time. Though the value of 3 sigma boundary is greater than 53 arcsec, 1 sigma boundary value correspond with NISS mission requirements.

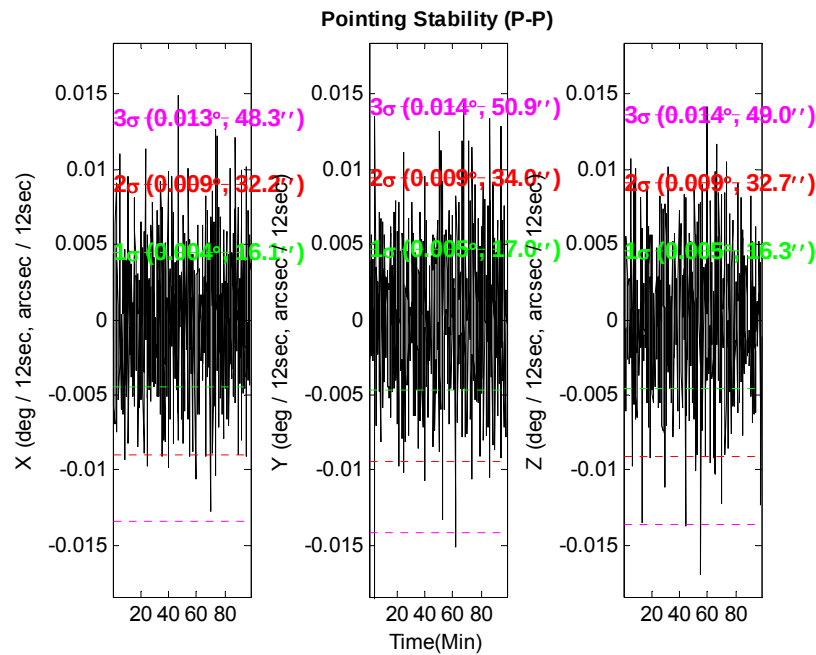


Fig. 14 Pointing Stability Results

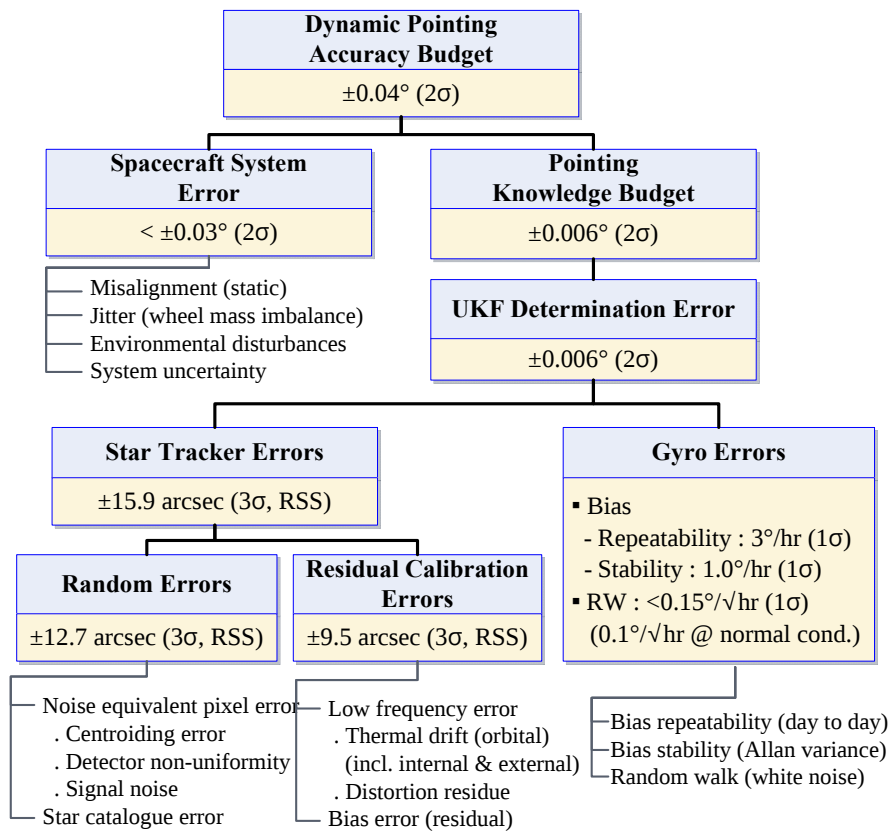


Fig. 15 Pointing Budget of NEXTSat-1

NISS agree to accommodate pointing performance of satellite bus but propose another requirement in that estimated attitude value should be transmitted to NISS electronics to remove noise factor due to pointing stability magnitude. ACS determines to provide attitude value, quaternion, periodically through CAN interface bus and NISS save the attitude data with science image. The acquired attitude data will be used to remove useless data which break away from allowable error range and to sort the effective data in error range during the image processing. NISS's science mission will be performed with this a series of process. Finally, the pointing budget of NEXTSat-1 is presented in Fig. 15.

4. CONCLUSIONS

In this paper, we introduced sensors and actuators modeling with designated specification parameters using standard theoretical analysis. Gyroscope and star tracker is the main sensors that determine the pointing performance of satellite. Reaction wheel is the main actuator that takes charge of the maneuvering of NEXTSat-1 and the analysis of all modeling work properly to evaluate performance of the satellite. To improve the reliability of analysis, two-body dynamics orbit modeling with respect to J2 perturbation and environmental disturbances model are included into total simulation. Unscented kalman filter is used to estimate attitude information with quaternion parameterization and quaternion feedback control logic is applied for satellite control with adequately selected parameters. Finally, pointing accuracy, knowledge, and stability performance are generated through integrating all models and parameters. Each performance is satisfying the related attitude control requirements of NEXTSat-1 and science payloads.

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